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SECURITY CLASSIFICATION OF THIS PAGE

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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S): ARO 26759.1-RH-EG
6a. NAME OF PERFORMING ORGANIZATION: Vanderbilt University / 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: U. S. Army Research Office
6c. ADDRESS (City, State, and ZIP Code): Nashville, TN 37203	7b. ADDRESS (City, State, and ZIP Code): P. O. Box 12211, Research Triangle Park, NC 27709-2211
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: U. S. Army Research Office / 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: DAAL03-89-G-0015
8c. ADDRESS (City, State, and ZIP Code): P. O. Box 12211, Research Triangle Park, NC 27709-2211	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification): Workshop on ESD Ignition of Composite Solid Propellants

12. PERSONAL AUTHOR(S): A. M. Mellor

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
final	FROM 2/1/89 TO 1/31/90	Jan 1990	

16. SUPPLEMENTARY NOTATION: The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Electrostatic Discharge Ignition, Propellants, Composite Propellants, Solid Propellants, Ignition

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

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(Continued on reverse side)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION: Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE: UNCLASSIFIED

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WORKSHOP ON ESD IGNITION OF COMPOSITE SOLID PROPELLANTS

WORKSHOP SUMMARY: ESD IGNITION OF COMPOSITE SOLID PROPELLANTS

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ABSTRACT

A mechanism for an electrostatic discharge (ESD) initiation of a solid rocket motor is presented, based largely on discussions at a recent workshop focussed on ESD ignition of composite propellants. Electrical property measurements and breakdown phenomena have enjoyed most attention to date and did at the meeting as well. Here overviews of the formal workshop presentations are given, but the main emphasis is to convey the flow of the discussions, which included proposals on new ignition experiments now required, as well as preliminary thoughts on formulation of an ignition model. Based on the informal discussions, a recently proposed, detailed physical mechanism for ESD ignition is modified somewhat to be more consistent with experimental observations.

INTRODUCTION

Recent progress in the electrical modeling of composite solid propellants has indicated microarcs can occur between $A\ell$ particles if the charge distribution on the bulk propellant is sufficient (Larson et al., 1989). It is believed these microarcs are necessary precursors to electrostatic discharge (ESD) throughout the propellant and potentially can induce local ignition. If the material retains its integrity for a sufficient time after local ignition, to provide confinement, then flame spreading can occur as the pressure builds locally, resulting in ignition

[a]Work supported under Grant DAAL03-89-G-0015 with the Army Research Office.
[b]Work supported under Contract DAAL03-87-C-0021 with the Army Research Office.

and combustion of a significant amount of propellant. Larson et al. (1989) and Reuter and Church (1989) discuss the two major accidents since 1985 involving solid propellant rocket motors and attributed to ESD initiation.

The present workshop was prompted by the need to couple these microarcs to local ignition models in order to predict at least the first step of the processes leading to combustion. Specifically, invitees were asked to respond to the following questions. If the local electric field strength is obtained from knowledge of the applied charge and through assuming a random distribution of oxidizer and metal particles, each with known size distributions, and if microarcs between the latter occur, what local criterion in terms of energy, duration, and spatial extent of the microarc will predict a sustained ignition of the propellant as a whole? How can effects due to the confinement of the surrounding propellant be modeled? Are there models currently available to describe the internal ignition of composite propellants via the mechanism just described? Do these need further development or validation, or is a new model required?

The meeting organization selected to address these questions is given in the agenda which follows this summary. A list of final participants is included at the end of the workshop proceedings. In this review, we only highlight the formal presentations which were made (abstracts and most viewgraphs used are reproduced after the agenda). Instead, we stress the discussions which were interspersed throughout the meeting and the conclusions reached. The former focussed upon measurements required for the models; status of present measurement techniques; comparisons of models and experimental results to date; and new models and experiments which are required.

There has been considerable work in the past on dielectric breakdown of composite solid propellants and some on charge and electric field generation (see for example Larson et al., 1989), and the discussion in the present summary concentrates upon this as well as the original workshop issues. Thus propellant ignition via arcs or sparks, and models or mechanisms pertaining thereto, are emphasized. Accordingly, we begin with a brief survey of the invited

formal presentations.

The first three were overviews: Williams (1989) reviewed the various types of electrostatic discharges observed in air, the hazard represented by each as determined by literature measurements with fuel gases, vapors, or dusts in air, and where each could occur during solid propellant processing. The background for the current workshop was provided by Larson and Beale (1989). Because charge generation is known highly dependent on ambient temperature and humidity, measurements of this process for a particular situation are preferred to models, but models of the resulting breakdown can lead to the predicted microarc sequence between $A\ell$ particles dispersed in a propellant. Based on studies of static charge generation and transport, and breakdown measurements for various propellants as observed in the French test (Kent and Rat, 1982), Reuter and Church (1989) reviewed an ESD protection plan, using proper materials selection and grounding procedures during propellant or motor handling, and personnel training now in use. Interestingly, Larson and Beale (1989) noted that it is unclear from an electrical modeling point of view why ESD breakdown occurs more readily at reduced ambient temperatures.

Two micromodeling papers were presented next. Shaeffer and Faulkner (1989) offered a fractal model with an equivalent circuit basis (using batteries in some cases) to explain the multitude of RC time constants observed experimentally with propellants and to relate electrical properties to percolation theory (Kent and Rat, 1982). A powerful new method using a "dimension–reducing trick" simulates random spherical particle packing, as discussed by Davis et al. (1989). Local electrical (or mechanical) stress fields are then calculated by iteration based on orthogonal expansions in terms of spherical harmonics.

All of the papers which followed were concerned with experimental methods and results. These included improved measurements of arc voltage (Schneider et al., 1989) and current (Lee et al., 1989), as well as of propellant volume resistivity, dielectric constant, and loss index at high frequency (Dean and Williams, 1989). Arc details are crucial for power and energy measurements to the propellant sample, as will be discussed below, and errors in measured

voltages using commercially available instrumentation occur because magnitudes of interest in the circuit used for breakdown or ignition experiments differ widely and fluctuate during the arcing process (Schneider et al., 1989). Dean and Williams (1989) characterized electrical properties, at frequencies corresponding to the short times involved in breakdown and discharge, for several propellants at controlled ambient temperature and humidity. Among their results were observations that propellants with HTPB binder exhibit higher rates of energy dissipation and the size of spherical $A\ell$ (or AP) has little effect on electrical properties, although the shape of the former is extremely important.

In devices to simulate core–pulling during Peacekeeper motor manufacture, Magann (1989) studied effects of ESD, friction, and confinement on ignition of the propellant (as defined by popping sounds upon application of the stimuli); because pressure buildup could be sufficient to relieve the applied confinement, flame–spreading and total propellant consumption (and thus severity of the event) were not addressed (Magann et al., 1989). Observations included ESD ignition energies on the order of 0.1 mJ at pressures of 6.4 atm; a fresh, non–scratched teflon coat on the electrodes prevented any ignition at available experimental power levels; and, at sliding velocities up to and equaling 0.5 mm/s, friction on steel or damaged teflon–coated steel had no effect. In the configuration employed, designed to simulate motor manufacture, propellant confinement was provided by bulk electrodes. Because the propellant tended to extrude at higher pressures, confinement and sample size could not be varied independently (Magann, 1989).

In other ignition experiments with explosives containing $A\ell$, RDX, and AP, Lee et al. (1989) observed that most energy deposition occurs during, not prior to, breakdown. For their materials no reaction was found unless breakdown had occurred, at which time spectroscopy for surface products (not sensitive to $A\ell$) showed substantial decomposition of the AP and only some RDX reaction. Covino (1989) ranked four rocket propellants in terms of computed percolation coefficient (see e.g., Kent and Rat, 1982), measured electrical properties, burning rate, and spark and thermal ignition threshold (the latter in terms of CO_2 laser surface heat

flux for sustained ignition). Only the latter two parameters corresponded qualitatively, suggesting that ease of breakdown is not indicative of ease of ignition. The final paper (Mellor et al., 1989) proposed a new experiment using subsurface thermal ignition directly (via hot and exploding wires) as a baseline for comparison with spark ignition measurements on solid propellants. The method includes independent variations of sample size and confinement, and recommendations for obtaining minimum (spark or thermal) ignition energies, generally considered properties of a combustible medium (Mellor et al., 1988).

In the following section we discuss dielectric breakdown and ESD ignition, major topics addressed and distinguished between throughout the workshop. Ignition measurements refined over present techniques are covered in the third section. No fundamental ESD micro–ignition models were identified, but preliminary thoughts examined during the discussions are summarized prior to the final section concerning general workshop conclusions. As will be seen, much of the speculation revolves around establishment of a physical mechanism for the processes following microarcs, that is, the sequence of events leading to sustained ignition and substantial combustion and consumption of the propellant.

DIELECTRIC BREAKDOWN VERSUS IGNITION

Having defined and obtained results from the French test methodology for ESD sensitivity (in terms of electric breakdown but rarely sustained ignition), Kent and Rat (1982) proposed the following mechanism, that the applied voltage (or field) leads to microarcs, involving local breakdowns of $A\ell_2O_3$ layers on the $A\ell$ particles within the propellant. Cracks appear at this point, and the volume resistivity decreases significantly. If sufficient energy is then deposited in the material, ignition will occur. Thus breakdown requires a threshold applied voltage, and ignition indicates a substantial subsequent threshold energy flux.

Because Larson et al. (1989) and Larson and Beale (1989) included triboelectric charge generation as the necessary first step in an ESD incident involving rocket motors, their mechanism begins at this point, as shown in Table 1. Charge generation (Part A) is followed by mechanical charge separation, as in an accident, which generates the electric field (Part B).

The latter area is amenable to so–called macromodeling (Larson et al., 1989; Larson and Beale, 1989), which through finite difference, finite element, boundary element, multipole expansions, or equivalent circuits appears reasonably successful. Hodges[c] and Larson et al. (1989)

Table 1. Summary of Physical Events Involved in an ESD–Caused Ignition, Parts A and B (from Larson et al., 1989 and Larson and Beale, 1989)

A. At the microscopic level, the chain of events begins with:

1.	Polymer or insulator	(touching a triboelectrically active material:)
2.	Teflon	(to produce, via)
3.	Triboelectricity	(the contact charge generation mechanism)
4.	Original Charges	(about 10 microcoulombs/square meter)

B. Which, at the macroscopic level, are separated by

5.	Force	(from some lifting mechanism, which causes)
6.	Movement	(of the charges, thereby causing a decrease in)
7.	Capacitance	(inversely proportional to separation, to produce)
8.	High Voltages	(and <u>may</u> thereby generate <u>other</u>)
9.	Electrical Charges	(which acting over)
10.	Short Separations	(inches or fractions of an inch, create)
11.	Peak Electric Field	(on the order of 100–1000 kilovolts/m, and adequate)
12.	Energy	(stored in grain fields, which). . .

discuss experimental techniques to accurately measure the electric fields which are created in motors. A planar capacitance meter, suitably corrected, is recommended.

It was noted previously that no original charge generation models can be expected to accurately predict effects of temperature, relative humidity, and so forth. Dagonese suggested more work is appropriate on charge state generation through surface contact (seconded by Shaeffer) and that Xerox has done substantial study of polymer–polymer contact. Davis mentioned the work of Dickinson at Washington State University in this regard, and Losee indicated Hercules has Utah State University under contract reviewing other literature on

[c]The use of a surname without date will indicate a contribution during informal workshop discussion. No further reference is listed at the end of this paper. See pp. 145–148 of this proceedings for a list of all attendees and their affiliations.

triboelectrification to develop fundamental understanding of both triboelectric effects and dielectric breakdown in solids. Dagonese's concern is understanding the relevant charging of propellants in contact with (thermal) insulators and other materials present in the motor environment.

Table 2 continues the mechanism begun in Table 1 (Larson et al., 1989; Larson and Beale, 1989) into the microarc and breakdown phases, with clarification of the first part of Kent and Rat's (1982) model. Propellant cracking, due to local ignitions resulting at the microarc locations, not indicated in Table 2, may precede creation of the discharge path. Modeling of the microarc sequence requires large amounts of computer time (and cost) for dealing with the large numbers of $A\ell$ particles (Larson et al., 1989; Larson and Beale, 1989); alternative approaches, such as percolation theory and those suggested by Shaeffer and Faulkner (1989) and Davis et al. (1989) should be pursued as well. The electrical microarc model may require extension to multimodal particle size distributions and nonspherical $A\ell$ particles (Dean and Williams (1989) show the electrical properties, and thus possibly ignition thresholds, are quite different for propellants including flake rather than spherical $A\ell$).

As noted, the model of Davis et al. (1989) predicts local mechanical stress fields (and perhaps could be extended to include cracking) in addition to electrical fields. Dienes pointed out that existing delayed detonation (XDT) codes must and do model propellant cracking.

Table 2. Summary of Physical Events
Involved in an ESD–Caused Ignition, Part C
(from Larson et al., 1989 and Larson
and Beale, 1989)

C. At the microscopic level, because of:

13.	Field Amplification	(on the order of 1000, due to)
14.	Close Spacing	(angstroms separation, of)
15.	Aluminum Particles	(about 20% by volume, in)
16.	Propellants	(with AP and binder, causes a)
17.	Point Breakdown	(an avalanche effect at a high E–field point, through)
18.	Alumina Layers	(also angstroms, which then goes on to create a)
19.	Discharge Path	(which, given the correct conditions). . .

Isom offered a mechanism for this portion of ESD ignition based on observations of dissected, cracked French test propellant specimens subjected to multiple discharges. Local damage occurs under the upper, pointed electrode used in the test (Kent and Rat, 1982), but is generally unconnected to the other cracks. Church asked if the same fracture pattern is seen if an identical propellant and specimen is subjected to a point impact where the upper electrode abuts, which was followed by brief discussions of high frequency vibrations and piezoelectric effects in the French test, the results of which are not easily interpreted.

The potential effect of voids in the propellant on cracking, breakdown, discharge and ignition introduced a flurry of controversy and brought out the following points, some contradictory: 0.25% is the maximum allowed for quality control – Davis; AEDC accepts up to 6 to 13 mm voids by X–ray analysis before declining to test hardware; voids filled with H_2, not $A\ell$ particles are more important to local ignition – Larson in reference to work at Aerojet; there is no change in observed breakdown voltage for a propellant with or without voids – Losee; Lee disagreed and notes there are always voids present in explosives. Microvoids would not be visible in X–ray images and would significantly alter breakdown strength.

After the discussion chairman regained control, Isom continued by noting that where fresh propellant surface was exposed by the large cracks, perhaps it could be concluded that microarcs had occurred, based on the observations of surface deposits and microcracks originating at a point. Thus Isom postulated the sequence is a microarc which causes local ignition and then cracking, consistent with the mechanism of Kent and Rat (1982). Depending on the ability to maintain the pressure increase locally (confinement), sustained ignition, flame spreading, and total combustion could result, but evidently for Isom's self–quenched specimen did not.

For this particular sample, Isom could see no evidence of any continuous arc path, in contrast to the Larson–Peale model which at the present omits propellant fracture and chemistry. It is unknown if an inert propellant with similar electrical and mechanical properties (AP replaced by inert particles of same size distribution) would exhibit the same

type of fracture pattern and deposits: Gibson (1989) has studied $A\ell$–binder in a French–like test and found no evidence of cracking, which supports the mechanism discussed above because no chemical reactions can occur.

The final portion of the Larson et al. (1989) ESD ignition mechanism is reproduced in Table 3. Recall the distinction between local ignition and sustained ignition, which (due to confinement?) results in substantial combustion of the available propellant (Mellor et al., 1989; Hermance). Here the relations between deposited energy, spark duration, and spark spatial extent, defined in the workshop invitation, as well as the relation between the energy in a microarc and the minimum spark ignition energy (Mellor et al., 1989), enter the discussion. Alternatively, how many microarcs constitute an optimum spark (which by definition requires the minimum energy for ignition)?

The mechanism shown in Tables 2 and 3 is point breakdown (step 17) leading to a discharge path (step 19) and initial ignition (step 22). At this point, Isom notes that depending on confinement the propellant may or may not crack, a process not included in Table 2 or 3. High levels of confinement, either by external pressure or by large propellant samples (as in the French test), suppress cracking but support sustained ignition, followed by combustion. Thus, another distinction between the observations of Isom and Table 3 is local versus sustained ignition.

Lowest ignition energies are always observed with confinement (Magann, 1989) or equivalently, at high ambient pressures in work at Lockheed (Hodges, 1989). Thus, a decrease or prevention of venting through large cracks reduces the number of microarcs necessary for sustained ignition. The hot wire experiment proposed by Mellor et al. (1989) is more controlled and more easily modeled than the similar spark experiment and may thus simplify issues of propellant cracking and confinement (Dienes).

REFINED MEASUREMENTS

Further electrical property measurements are required to generate data needed for existing models. For example, Shaeffer listed volume resistivity and complex dielectric

Table 3. Summary of Physical Events
Involved in an ESD–Caused Ignition, Part D
(from Larson et al., 1989 and Larson
and Beale, 1989)

D. At the macroscopic level, including

20.	Time	(and energy and the right "circuit", leads to a)
21.	Temperature Profile	(along the surface of the discharge path, gives an)
22.	Initial Ignition	(which is exothermic, and given the right sort of)
23.	Pressure Confinement	(not present in most cases, eventually leads to)
24.	Total Combustion	(as "most probably" in the two accidents).

constants, also to include lower frequencies of 10^{-4} to 10^{-5} Hz, for binder plus AP, AP, and $A\ell_2O_3$ at various temperatures of interest. New data relevant to microignition are also highly desirable. In addition, there was both support for and controversy regarding the new experiments proposed by Mellor et al. (1989). The spark version brings to bear considerable prior work and experience with other combustible systems, and the thermal version is desirable for reasons discussed above, including modeling.

For each propellant, the required parametric variations are given in Mellor et al. (1989). In addition, an electrical circuit is envisioned with RC's available from 0.15 μs to 2 ms (Peters, 1981); a pressure vessel is recommended rather than simply increasing sample size for confinement studies. One unknown at this point is the lack of AP on a cast propellant surface, and how this may affect the hot wire or electrode environments. Mellor et al. (1989) could not conceive a solution to this problem, also pointed out by Magann.

Somewhat similar work is underway at Lockheed (Hodges, 1989). However, in those studies gap width is not varied, the external circuit allows only two spark durations, and the samples may be damaged in the act of electrode insertion. Nevertheless, the Lockheed program to date is an important contribution. Measured spark ignition energies for propellants are at high pressure two to three times those shown in Mellor et al. (1989) for 40 μm n–heptane droplets in air at standard conditions with equivalence ratio of 0.7.

The improved voltage and current measurements discussed previously could be incorporated in either experiment if necessary to eliminate errors using commercial high voltage probes, as suggested by Schneider et al. (1989), and obtain current directly with a Rogowski coil (Lee et al., 1989). If electrical models for the spark versions are constructed, then concerns and issues can be addressed such as first, the positive column length (a function of external circuit design and applied power level) versus the gap width in solids (Lee et al., 1989; Smith); second, transient effects in the arc (Smith); and third, electric field enhancement at the hemispherical electrode tips (radius order 0.5 mm in Mellor et al., 1989; "needles" at Lockheed) versus that at the $A\ell$ particles (radius order 10 μm), discussed by Hodges.

As improved methodology is demonstrated, then the consensus on propellant variables which must be studied independently for propellant spark ignition thresholds includes 1) $A\ell$ and AP loading; 2) binder type; 3) monomodal diameter of $A\ell$ and AP; 4) multimodal size distributions of $A\ell$ and AP; 5) flake versus spherical $A\ell$; 6) coated $A\ell$ particles; 7) $A\ell_2O_3$ film thickness on $A\ell$; and so forth.

ESD IGNITION MODELS

Hermance stated that most needed for ESD ignition predictions are microstructure simulations, as discussed by Davis et al. (1989), which will take a model from one propellant to a different formulation, and relevant electrical properties. Because ESD predictions based solely on thermal ignition require the size and geometry of the arc with respect to the various length scales of the propellant formulation, there exist links with both the microarc analysis of Larson and Beale (1989) and the minimum ignition energy estimates discussed previously (Hermance). He noted in addition an expectation of the importance of binder decomposition as the first step in the process, because it is generally thought AP decomposition by itself is insufficient for sustained ignition. The discussion closed with Dienes again suggesting the hot wire experiments as easier to model than spark experiments.

CONCLUSIONS

Relative lengths of the previous sections suggest that much discussion at the workshop focussed on dielectric breakdown and its connection to sustained ignition, with considerably smaller attention on required new experiments. Even less time was spent on ignition modeling. In itself this emphasis accurately reflects past and current work and thinking on electrostatic discharge ignition of composite solid propellants, largely oriented toward identification of a plausible scenario for accidental rocket motor initiation by ESD. One goal of the workshop was to summarize the present understanding, adequately represented in the viewgraph presentations which follow.

Several more specific points and conclusions bear repeating or mentioning. Electrical property measurements alone do not indicate the result of an ESD stimulus on a solid propellant (Covino, 1989). Mann noted the disparate magnitudes between reported values of energy for breakdown, minimum ignition energy, and predicted microarc energy and concluded the issues must be resolved. Lee responded that breakdown is a necessary, but not sufficient condition for sustained ignition.

A second goal of the workshop was to move the attention of the ESD research community away from electrical breakdown studies toward developing an understanding of the ESD ignition process itself. Kent and Rat (1982) offered a concise sequential mechanism consisting of microarcs, cracking, breakdown, and possible ignition. In Table 2, the more detailed mechanism postulated by Larson et al. (1989) and Larson and Beale (1989) for the breakdown portion of the overall process begins: microarcs, breakdown, and in Table 3 (for ignition), local ignition followed by sustained combustion, provided sufficient propellant confinement exists.

An alternative scenario is that discussed by Isom in which a microarc produces local reaction (or local ignition). Combustion products at high pressure released at that position interior to the propellant crack the propellant as they vent to the ambient. If confinement is adequate, the venting is inhibited (and perhaps the cracking too) so that other microarcs,

complete breakdown, and flame–spreading occur, although not necessarily in that sequence. With minimal confinement, the venting may extinguish the local reaction after the cracks form (still considered a positive reaction to ESD in the French test). This mechanism is similar to that of Kent and Rat (1982), but includes the important effect of confinement.

Certainly additional electrical property/modeling questions remain. Shaeffer raised issues such as non–linear effects, diode effects versus multiple RC time constants for propellants, charge storage in propellants, and extent of ionic as opposed to electronic conduction as well as piezoelectric effects, both for AP. From the ignition modeling point of view, little has occurred (see also Larson et al., 1989). The physical mechanism outlined above suggests that a microarc reaction model could estimate local gas generation rate and pressure in the cavity formed by the microarc. Knowledge of microstructure and mechanical properties, with perhaps some borrowing from XDT analysis techniques, may predict if cracks originate at the microarc/local reaction position. Finally, flame–spreading models for cracked or damaged propellant could be used to predict extinguishment or sustained ignition. Because the last two steps are of significant interest in scenarios other than ESD, our task is not as formidable as it might appear.

Regarding the suggested new experiments, Lee complained that none replicate the charging of a propellant in a motor environment as thought to have occurred in the recent incidents. Rather, they impose a spark on, around or through a propellant. Is the distinction important? This question has not been resolved. However, work to date, as itemized in the presentation summaries which follow, has brought us to the next generation of experiments and models proposed and discussed at the workshop, and yet required to address an ESD–munition incident from start to finish.

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ARMY RESEARCH OFFICE

WORKSHOP ON ESD IGNITION OF COMPOSITE SOLID PROPELLANTS

AGENDA
April 18-19, 1989
Vanderbilt University
Nashville, Tennessee

April 18, 1989

0800-0830	Registration
0830-0845	Welcome G.E. Cook, Vanderbilt University
	Introduction D.M. Mann, Army Research Office

I. Session Chairman, D.M. Mann, Army Research Office

0845-0930	Microstructural Modeling of Electrical Breakdown in Solid Fuel Propellants R.W. Larson, Electro Magnetic Applications, Inc.
0930-1000	Coffee
1000-1045	Evaluation of Hazardous Electrostatic Discharges G.M. Williams, Hercules Inc., Allegany Ballistics Laboratory
1045-1130	Ballistic Missile Electrostatic Control Program R.A. Church, TRW, Ballistic Missiles
1130-1300	Luncheon

II. Session Chairman, A.M. Mellor, Vanderbilt University

1300-1330	A Fractal Approach to Modeling Electrostatic Discharge in Propellants D.L. Shaeffer, Physics International
1330-1400	Electric Field in a Concentrated Dispersion of Spheres I.L. Davis, Morton Thiokol, Brigham City
1400-1430	Discussion: Required Measurements for Models R.W. Larson and D.L. Shaeffer, Leaders
1430-1500	Coffee

AGENDA (Continued)

1500-1530	Evaluation of Propellant Hazards Using High Frequency Electrical Property Measurements G.M. Williams, Hercules Inc., Allegany Ballistics Laboratory
1530-1600	Conduction in an Aluminized Explosive During ESD R.J. Lee, Naval Surface Warfare Center
1600-1630	Measurement of Energy Content of an Electric Arc R. Schneider, Physics International
1630-1700	Combined Stimuli Solid Propellant Hazards Testing T.F. Magann, Morton Thiokol, Brigham City
1800-1900	Reception

April 19, 1989

III. Session Chairman, D.R. Dreitzler, Army Missile Command

0830-0900	Electrostatic Discharge (ESD) Sensitivity as Related to Combustion Characteristics J. Covino, Naval Weapons Center
0900-0930	Rocket Propellant Hot Spot Ignition Simulation A.M. Mellor, Vanderbilt University
0930-1000	Discussion: Present Measurement Techniques R.J. Lee, Leader
1000-1030	Coffee
1030-1115	Discussion: Models vs. Experimental Data to Date D.R. Dreitzler, Leader
1115-1200	Discussion: New Models and Experiments Required D.R. Dreitzler, Leader

MICROSTRUCTURAL MODELING OF ELECTRICAL BREAKDOWN IN SOLID FUEL PROPELLANTS

by

Ronal W. Larson
Paul D. Beale

ELECTRO MAGNETIC APPLICATIONS, INC.
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(303) 980-0070

ABSTRACT

As work has been performed on the electrostatic breakdown and ignition of solid propellants over the last four years, it has become clear that there are good macroscopic and microscopic reasons for Electrostatic Discharge (ESD) to be a serious hazard for solid propellants. Based on both static and transient macroscopic simulations, it is now well appreciated that the propellant fields from realistic charge densities can sometimes exceed those known to cause breakdown in small samples. From a modeling standpoint, the macroscopic analysis of the field distribution is not simple, but good accuracy is possible, and there are few doubts that hazardous situations can occur.

From a microscopic viewpoint, microscopic modeling is able to explain, primarily through the statistical details of the proximity of the aluminum particles, many of the experimental breakdown variations. However, the details of the behavior of propellant breakdown fields, conductivity, and permittivity as a function of time (or frequency) and temperature are not yet completely understood. This talk will primarily describe the present state of understanding in microscopic modeling and thereby address the theoretical bases for experimental results of two types: (1) low voltage, essentially linear measurements of resistivity and permittivity, and (2) high voltage breakdown field measurements (some ending in ignition).

A brief overview will first be given of the four major parts of the breakdown phenomenon. This will be followed by a description of a number of modeling techniques and results that are primarily useful in macroscopic modeling, but with emphasis here on their use in microscopic modeling. The major portion of the talk will deal with percolation theory results for a simplified two-dimensional model, followed by a discussion of extensions that will soon be implemented for spherical particles. Lastly, there will be a brief discussion of miscellaneous topics dealing with (among other things) effects of time (or frequency), propellant formulation, temperature, pressure, and relative humidity.

Slide 1a

MICROSTRUCTURAL MODELING OF ELECTRICAL BREAKDOWN IN SOLID FUEL PROPELLANTS

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Slide 1b

TOPICS TO BE COVERED

Slide	Section	Topic
2	2	Breakdown Mechanisms (Generation, Enhancements, Ignition)
3,4	3	Macroscopic Modeling (TDFD, FE, Quasistatics, Circuits)
5,6	4	Microscopic Modeling (Dr. Paul Beale)
7,8	6	Quasi-statics and other Examples
9	7	Conclusions, Status of Models
10	7	Comments from Modelers to Experimentalists

A. At the microscopic level, the chain of events begins with:

1.	Polymer or Insulator	(touching a triboelectrically active material:)
2.	Teflon	(to produce, via)
3.	Triboelectricity	(the contact charge generation mechanism)
4.	Original Charges	(about 10 microcoulombs/square meter)

B. Which, at the macroscopic level, are separated by

5.	Force	(from some lifting mechanism, which causes)
6.	Movement	(of the charges, thereby causing a decrease in)
7.	Capacitance	(inversely proportional to separation, to produce)
8.	High Voltages	(and <u>may</u> thereby generate <u>other</u>)
9.	Electrical Charges	(which acting over)
10.	Short Separations	(inches or fractions of an inch, create)
11.	Peak Electric Field	(on the order of 100-1000 kilovolts/m, and adequate)
12.	Energy	(stored in grain fields, which)

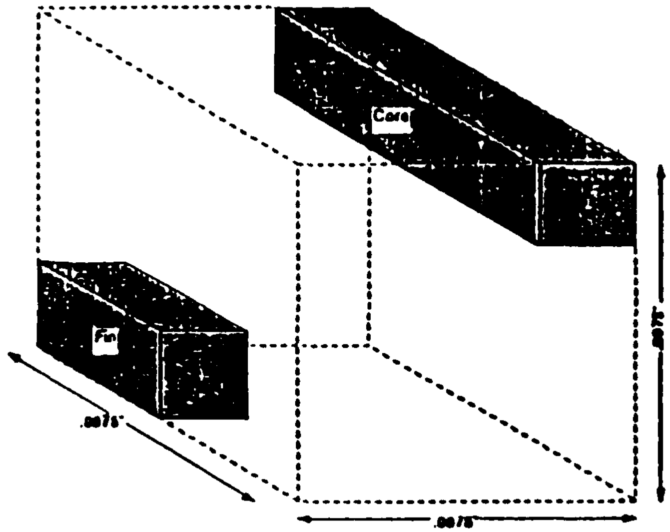
C. At the microscopic level, because of:

13.	Field Amplification	(on the order of 1000, due to)
14.	Close Spacing	(angstroms separation, of)
15.	Aluminum Particles	(about 20% by volume, in)
16.	Propellants	(with AP and binder, causes a)
17.	Point Breakdown	(an avalanche effect at a high E-field point, through)
18.	Alumina Layers	(also angstroms, which then goes on to create a)
19.	Discharge Path	(which, given the correct conditions)

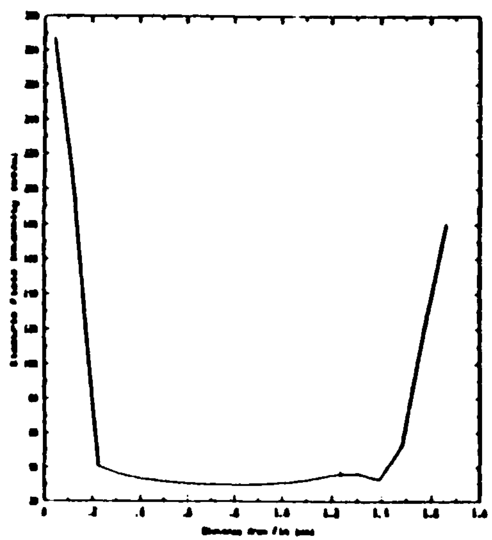
D. At the macroscopic level, including

20.	Time	(and energy and the right "circuit", leads to a)
21.	Temperature Profile	(along the surface of the discharge path, gives an)
22.	Initial Ignition	(which is exothermic, and given the right sort of)
23.	Pressure Confinement	(not present in most cases, eventually leads to)
24.	Total Combustion	(as "most probably" in the two accidents).

Summary of Physical Events Involved in an ESD-Caused Ignition

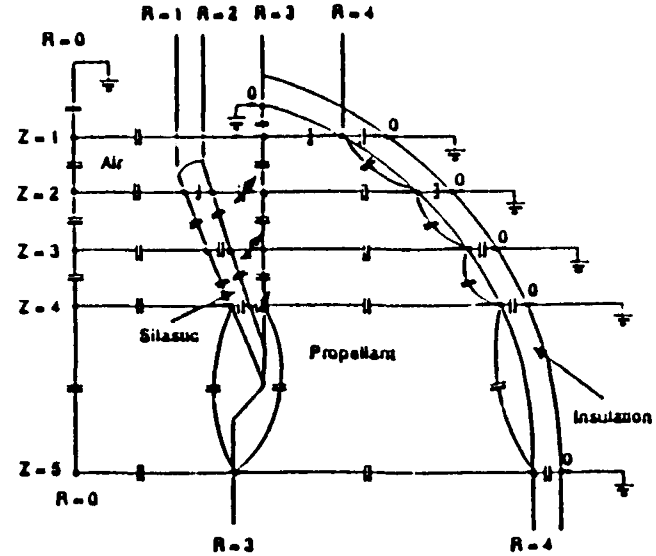


a. Three-Dimensional Gap Region

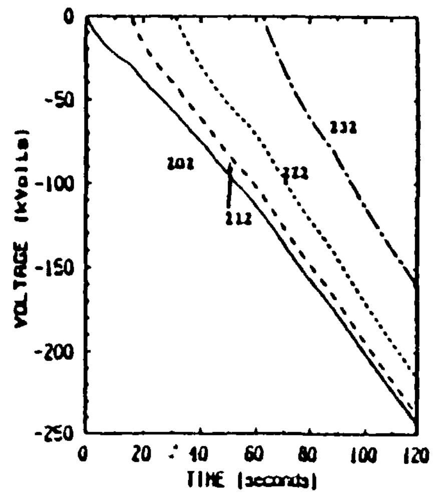


b. Electric Field Between Fin and Core

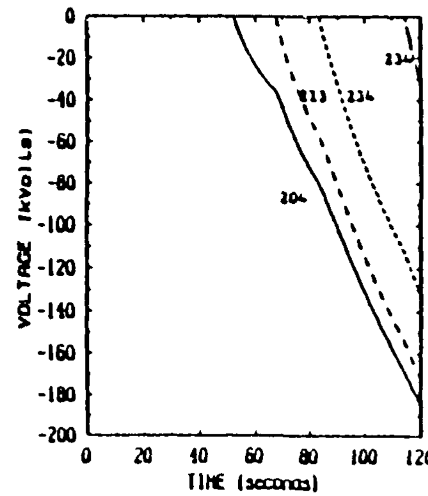
Typical TDFD Results for Three-Dimensional Small Gap



a. Sample Transverse Circuit at Constant Theta Plane

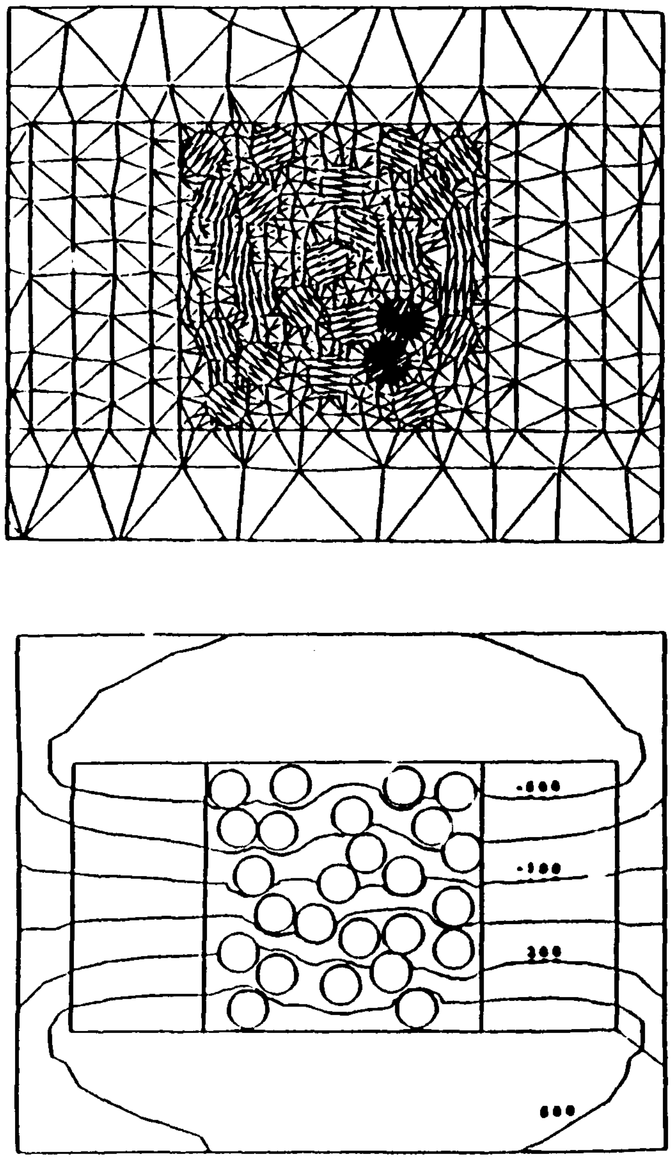


b. Upper (Z=2) Voltages

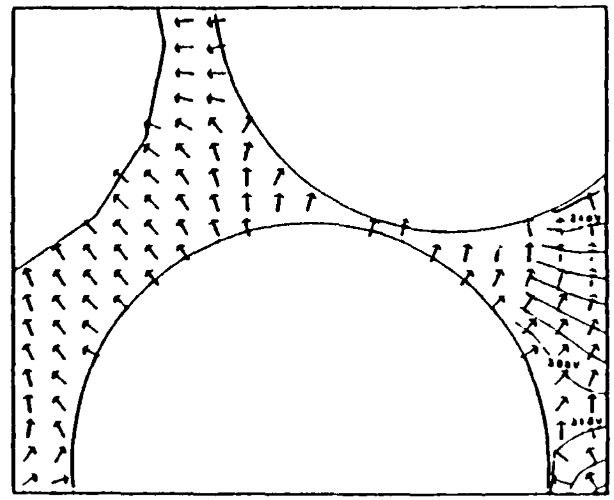


c. Lowest (Z=4) Voltages

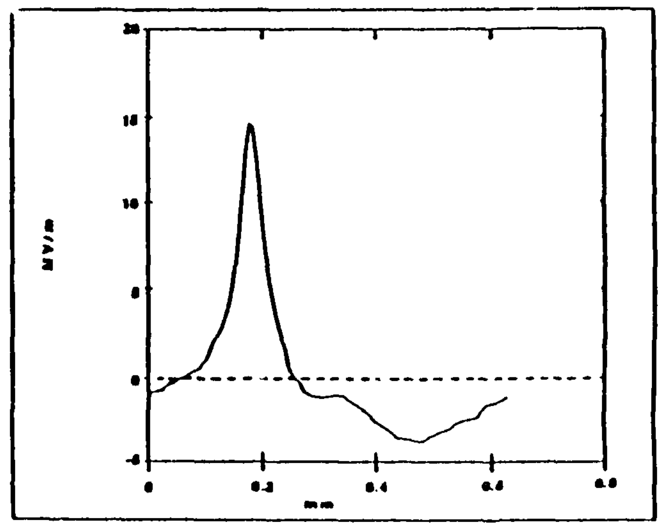
Simulation of Inward Removal of Rubber Core-Forming Part



Finite Element Simulation of 25 Randomly Placed Cylinders.
a. Mesh, b. Equipotential Plots



Vector Plot of Electric Field for Close-up of Portion of Figure 3.3a, with Equipotentials



(Cont'd) Derived Results from Figure 3.3b.
c. Flux Density, d. Electric Field Intensity

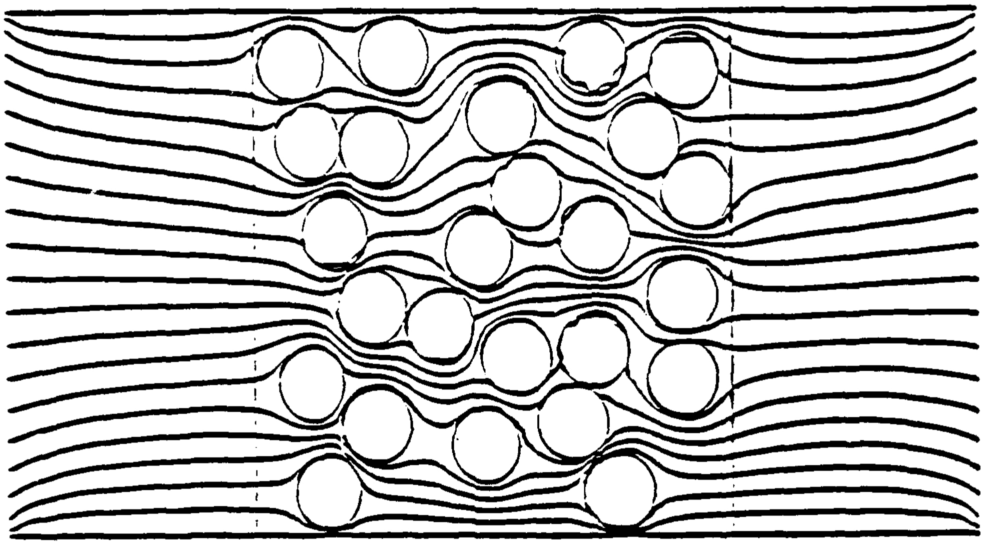


Figure 4.1 Equipotentials for a typical sample with an area fraction $\phi = 0.40$

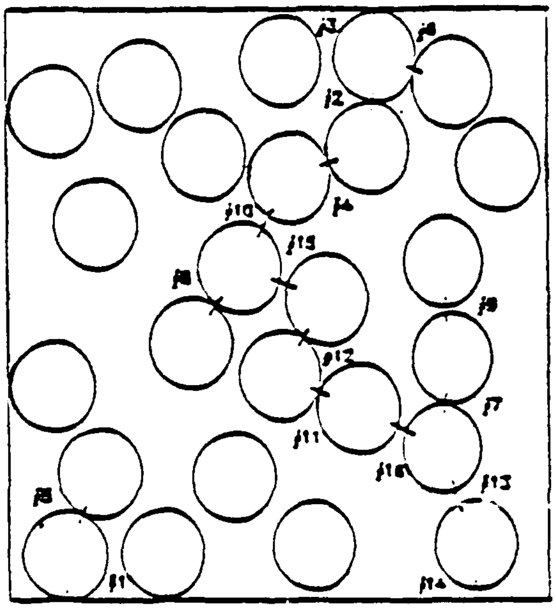


Figure 4.2a Breakdown sequence illustrated for a sample with $\phi = 0.40$

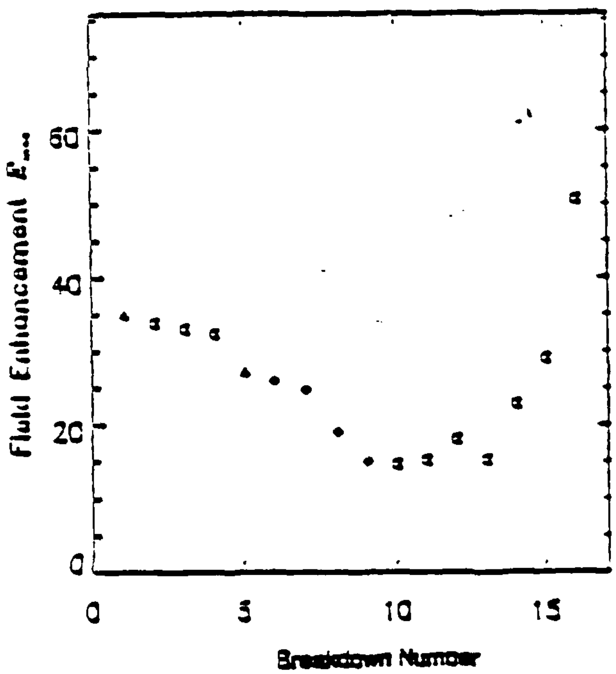


Figure 4.2b Maximum field enhancement vs. breakdown number for the breakdown sequence shown in Figure 4.2a. The squares represent connections that were on the final breakdown path, the diamonds represent dead end connections and the triangles represent isolated connections

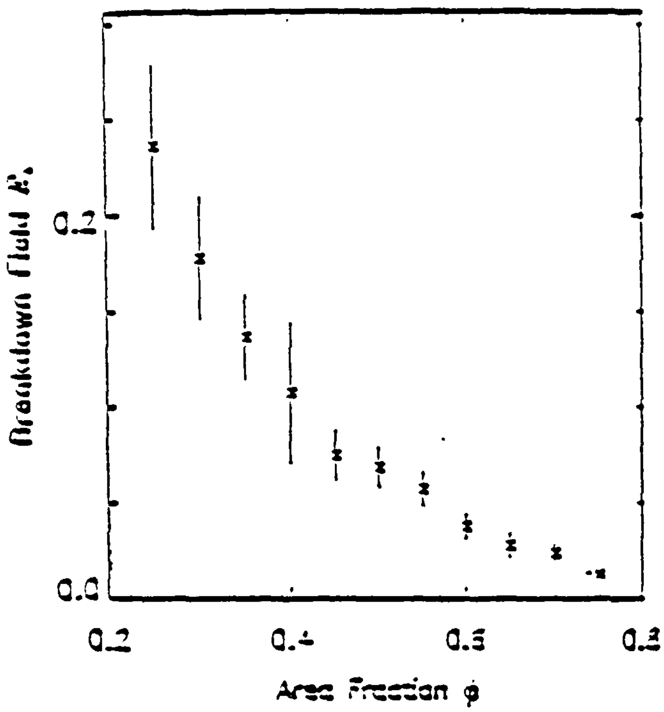


Figure 4.3 Breakdown field E_b vs area fraction ϕ_c

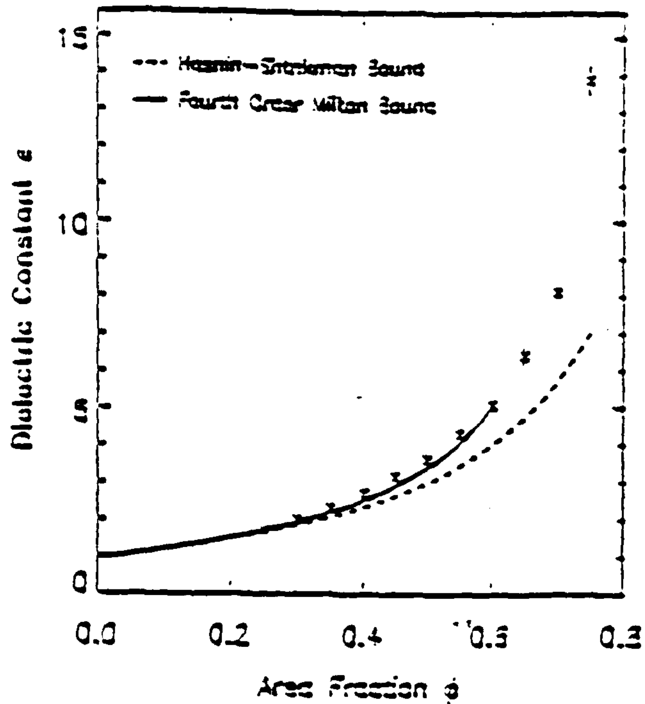


Figure 4.4 Effective dielectric constant ε vs fraction ϕ_c. The crosses represent our data

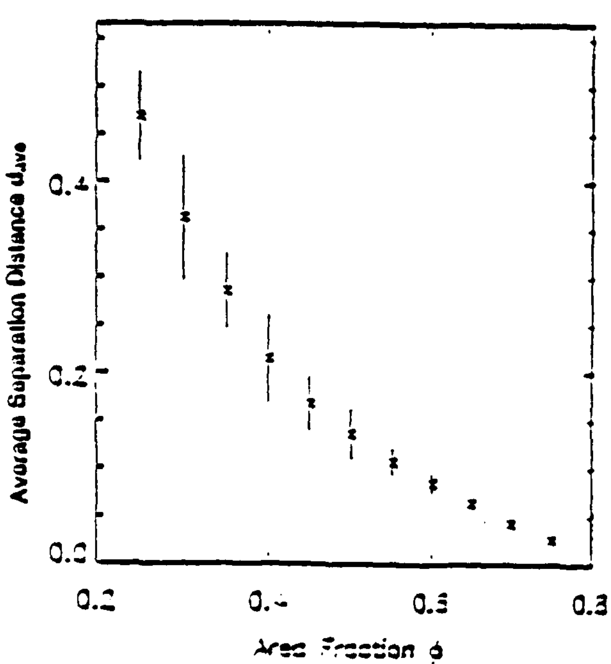


Figure 4.5 Average Separation distance d_{ave} vs area fraction

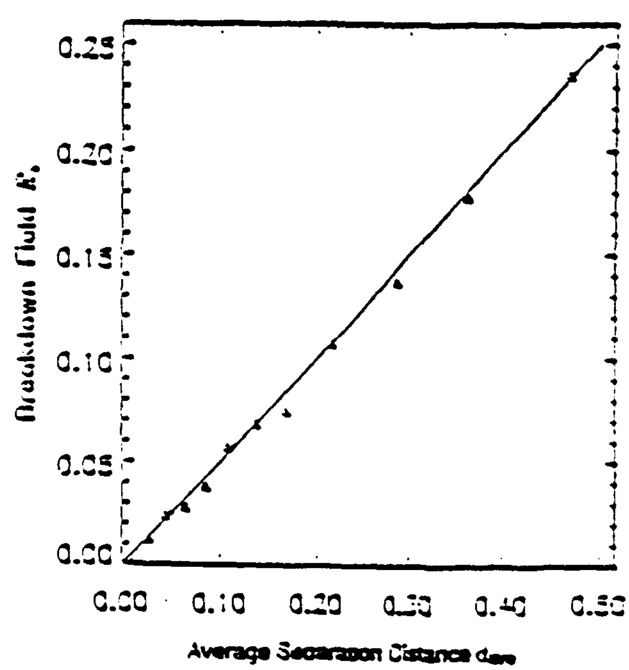


Figure 4.6 Breakdown field E_b vs average separation distance d_{ave}. The line shown has slope 1/2

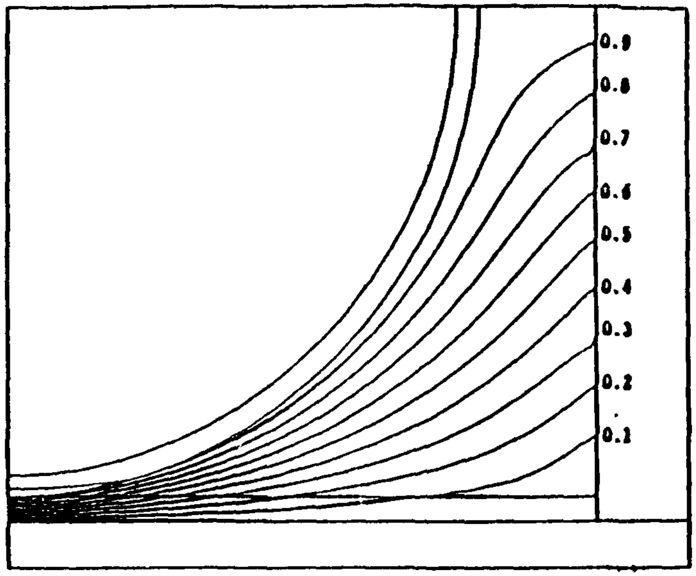


Figure 6.4a Equipotentials for Case 4, Early Time. 0.1 Volts Between *Contours*

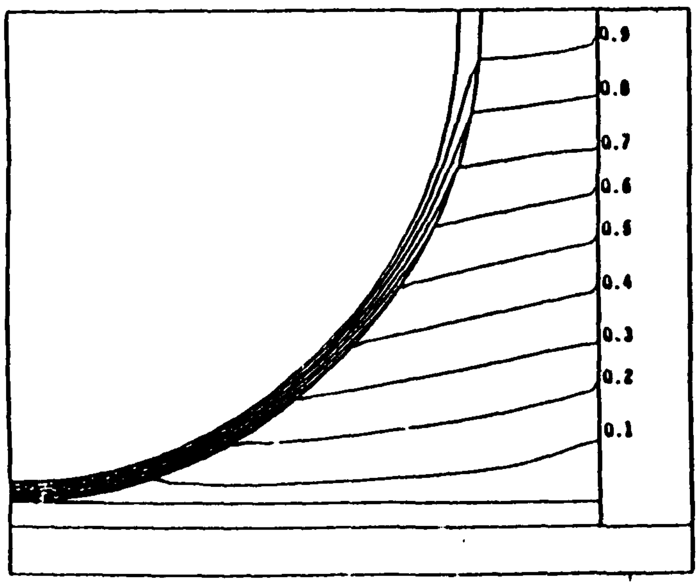


Figure 6.4b Equipotentials for Case 4, Late Time. 0.1 Volts Between Contours

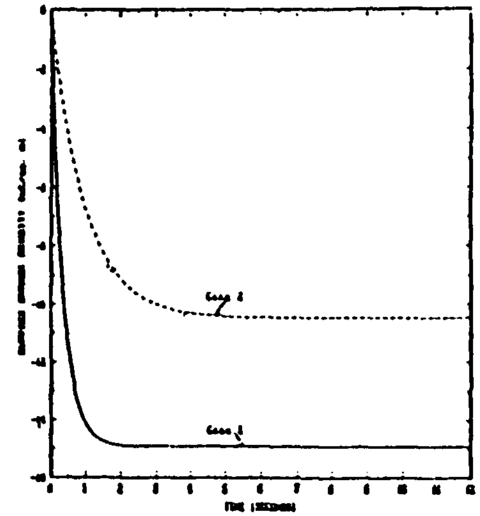


Figure 6.5 Solid Curve is Time History of Oxide/Binder Surface Charge *Density at Point at Closest Approach for Case 1.* Dashed Curve is for Case 2 (Between the States Shown in Figures 6.3a and 6.3b)

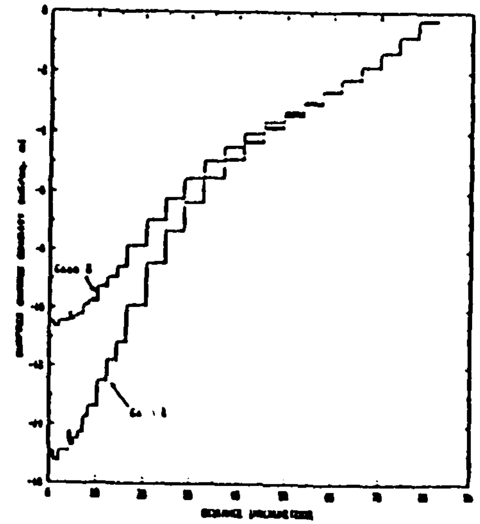
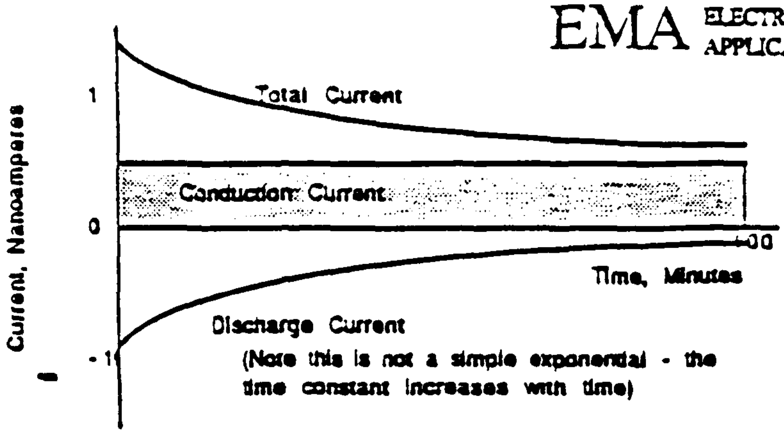
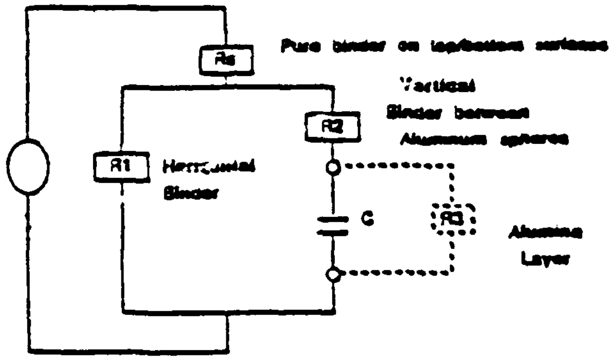


Figure 6.6 Late Time Oxide/Binder Surface Charge Density for Cases 1 and 2



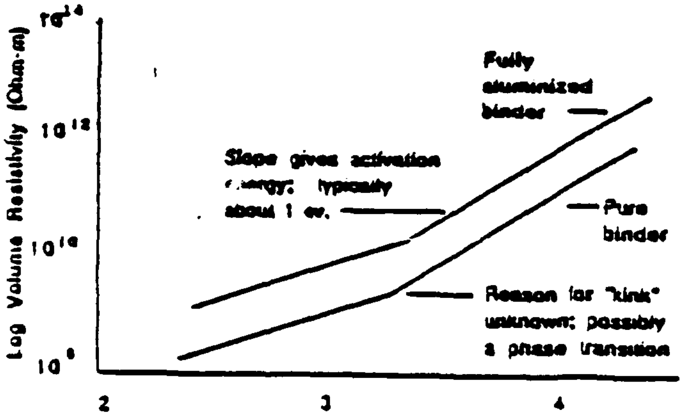
Typical Current Characteristics for Aluminized Propellant

Figure 6.8 Simulated Current Trace for an Aluminized Binder or Propellant



Equivalent Circuit for Aluminized Propellant

Figure 6.9 Possible Equivalent Circuit to Explain Measured V-I Characteristics of an Aluminized Binder (after Kraeutle [6.2])



Inverse Temperature (degrees Kelvin·10^{3})$^{-1}$

(Typical data - not drawn from experiment)

Figure 6.10 Log Volume Resistivity vs Inverse Temperature of a Typical Aluminized Binder or Propellant (after Kraeutle [6.2])

Slide 9a

CONCLUSIONS

1. Macroscopic analyses show that 10 microcoulombs per square meter placed on propellant surfaces or nearby dielectric surfaces can clearly be hazardous for some propellants.

2. The greatest single reason for the relatively small number of accidents appears to be the relatively low resistivity of many propellants; they are self protecting.

3. Microscopic analysis shows that breakdown fields are linearly related to average interparticle spacings in both highly structured and random 2-D arrays. The relationship is simpler than originally expected and expected to carry over to spherical particles.

4. The very low conductivity (high resistivity) of alumina can explain some breakdown experiments and some resistivity vs time experiments.

5. The temperature characteristics of reverse-biased diodes is very similar to many of the temperature characteristics of solid propellants.

Slide 9b

WORKSHOP ISSUES

	Question 1: Availability of Models	**Question 2:** Quality of Models
a. Electrical Models		
1. Charge Generation	None	N/A
2. Macroscopic Modeling	Many	Good-Excellent
3. Microscopic Modeling	Some	Fair
b. Ignition Models	Few	Need Work

Slide 10a

NEEDS OF MODELERS

a. Electrical Models

Macroscopic Modeling

1. Charge density measurements (a)
   - Use of coulometers (b)
   - Report fields, not voltages (c)
   - Use capacitance meters (d)

2. Field Computations
   - Need electrode shapes (e)
   - Spatial variations (f)

3. Breakdown
   - Relative humidity, temperature, etc (g)
   - Sample geometry (round, square, etc.) (h)
   - Surface resistivity

Slide 10b

NEEDS OF MODELERS, cont'd

Microscopic Modeling

Particles
- Size distribution (a)
- Prefer Volume distributions (b)
- Trace ingredients (c)
- Shapes (d)
- Specific gravities (e)
- Alumina thickness (f)

Micro-discharge Data (g)

Surface effects (h)

Slide 10c

NEEDS OF MODELERS, concluded

b. Ignition

Full circuit (R, L, C) details (a)
Physical dimensions of circuit elements (b)
Bandwidth limits of metering (c)
Means for distinguishing <u>minimum</u> energy (d)
Number of discharge paths (e)
Length and diameter of paths (f)
Pressure (p)

c. Other

Lightning
HPM
Statistics

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EVALUATION OF HAZARDOUS ELECTROSTATIC DISCHARGES

G. M. Williams
Hercules Incorporated, Allegany Ballistics Laboratory
Rocket Center, West Virginia

ABSTRACT

This presentation reviews the current understanding of electric field breakdown in air and in solid dielectrics as applied to solid rocket propellants. Electrostatic discharges in air (corona, brush, bulking brush, spark, propagating brush, and lightning) are ranked and classified according to their incendivity. These discharges are described and examined with respect to the necessary conditions for their occurrence. Breakdowns encountered in solid dielectrics are identified and discussed. Solid rocket propellant production processes are reviewed and conditions encountered which will be susceptible to hazardous electrostatic phenomena are indicated. An extensive bibliography was developed in this state-of-the-art review.

HERCULES

EVALUATION OF HAZARDOUS ELECTROSTATIC DISCHARGES

GEORGE M WILLIAMS
ALLEGANY BALLISTICS LABORATORY
ROCKET CENTER WV

DISCHARGES

- CORONA
- BRUSH
- DISCHARGES FROM PILES OF GRANULAR MATERIALS
- SPARK
- PROPAGATING BRUSH
- LIGHTNING

CORONA DISCHARGE

- EXTREMELY *INHOMOGENEOUS* FIELD
- CONDUCTIVE *GROUNDED* POINT AND
  CHARGED CONDUCTIVE OR
  NON-CONDUCTIVE SURFACE OR
  A CHARGED SPACE CLOUD
- *LUMINOUS* PHENOMENA AROUND POINT
- *CONTINUOUS* DISCHARGE
- RADIUS OF CURVATURE < *1mm*
- *LOW* ENERGY DISCHARGE
  - carbon disulfide
  - acetylene
  - hydrogen

BRUSH DISCHARGE

- *INHOMOGENEOUS* FIELD
- *GROUNDED* CONDUCTOR AND CHARGED CONDUCTIVE OR NONCONDUCTIVE SURFACE OR A SPACE CHARGED CLOUD
- *LUMINOUS* PHENOMENA - DOES NOT BRIDGE GAP
- *SEVERAL* DISCHARGES IN SUCCESSION
  -BRUSH APPEARENCE-
- RADIUS OF CURVATURE - *5mm*
- MAXIMUM EQUIVALENT ENERGY - *4mJ*
  IGNITES VAPORS
  DUSTS ?

DISCHARGES

FROM BULKED MATERIALS

- BULKING PROCESS
- INCREASES CHARGE DENSITY
- INCREASES ELECTRIC FIELD
- AIR BREAKDOWN EXCEEDED
- SURFACE DISCHARGES OBSERVED
- WIDE RANGE OF ENERGIES
- IGNITES DUSTS AND VAPORS

SPARK DISCHARGE

- VIRTUALLY *HOMOGENEOUS* FIELD
- DISCHARGE *BETWEEN* CONDUCTORS
- *LUMINOUS* PHENOMENA BRIDGES GAP
- *SUDDEN* DISCHARGE
- TYPICAL RADIUS OF CURVATURE
  - *5cm* -
- WIDE RANGE OF ENERGIES
  IGNITES VAPORS
  IGNITES DUSTS

PROPAGATING BRUSH DISCHARGE

LICHTENBERG DISCHARGE

- *INHOMOGENEOUS* FIELD
- LARGE DIAMETER *CONDUCTOR* AND HIGHLY CHARGED *NONCONDUCTIVE* SURFACE
- *LUMINOUS* EFFECTS
- DISCHARGES *30-40cm* DIAMETER AREA
- VERY ENERGETIC
  - *IGNITES* VAPORS
  - *IGNITES* DUSTS

DIELECTRIC BREAKDOWN

SOLID DIELECTRICS

- ELECTRONIC
- ELECTROMECHANICAL
- THERMAL
- GAS DISCHARGE
  - INTERNAL
  - EXTERNAL

ELECTRONIC BREAKDOWN

- INTRINSIC STRENGTH
- LIMITED KNOWLEDGE OF
  CONDUCTION PROCESSES
- CONDUCTION ELECTRONS
  FROM IMPURITY LEVELS
- RELIABLE MEASUREMENT
  RECESSED SPECIMENS
- PRE-BREAKDOWN CURRENTS
  ELECTRONIC CARRIER INJECTION
    - *ELECTRODES*
    - *IMPURITIES*

THERMAL BREAKDOWN

- JOULE HEATING
- RELAXATIONAL PROCESSES
- IN POLYMERS
  HIGH AMBIENT TEMPERATURES
  HIGH FREQUENCIES
- POWER DISSIPATED =
  RATE OF INCREASE IN HEAT CONTENT + RATE AT WHICH HEAT IS CONDUCTED AWAY

BREAKDOWN CAUSED BY
GASEOUS DISCHARGES

- DIELECTRIC STRENGTH OF GAS
  LESS THAN OF SOLID
- DISCHARGES LIKELY TO OCCUR
  EDGES OF ELECTRODES
  OCCLUDED BUBBLES
- THESE EXTERNAL OR INTERNAL
  DISCHARGES DAMAGE SOLID
- ORGANIC POLYMERS ARE
  ESPECIALLY PRONE
- PROCESS OFTEN ACCELERATED
  REACTION WITH OZONE OR
  HYDROGEN
  ACTIVE SPECIES FORMED
  IN GASEOUS DISCHARGE

The presentation will discuss the Peacekeeper ESD (Electrostatic Discharge) program initiated by the Air Force Ballistic Missile Office. The purpose of the program was to identify possible ESD hazards and implement mitigation designs and procedures.

The presentation is a broad overview of the program. It does not cover all the activities supported under the control program.

BALLISTIC MISSILE ELECTROSTATIC CONTROL PROGRAM

Robert W. Reuter, Lt. Col, USAF

Director, System Safety Engineering

Richard A. Church, TRW Ballistic Missiles Division

Norton Air Force Base, California

The material in this presentation is derived principally from four papers that have been given at JANNAF conferences. The material in these papers was supported as part of the Ballistic Missile Electrostatic Control Program

THE MATERIAL PRESENTED IS DERIVED FROM THE REFERENCES BELOW:

1. N. J. STEVENS, R. P. STILLWELL, A. ADICOFF AND C. S. UNDERWOOD, "ELECTROSTATIC DISCHARGE MODELING FOR SOLID ROCKET MOTORS," PRESENTED AT THE JANNAF PROPULSION SYSTEMS HAZARDS SUBCOMMITTEE MEETING, MARCH 1988.

2. R. P. STILLWELL, R. A. CHURCH AND W. N. CHRISTENSEN, "PEACEKEEPER STAGE I EMPTY MOTOR CASE SHEILDING," PRESENTED AT THE JANNAF PROPULSION SYSTEMS HAZARDS SUB-COMMITTEE MEETING, MARCH 1988.

3. R. A. CHURCH, A. ADICOFF AND R. P. STILLWELL, "CONCERNS WITH USE OF SOME PURPORTED STATIC CHARGE ELIMINATION PROTECTIVE PLASTIC SHEETING," PRESENTED AT THE JANNAF PROPULSION SYSTEMS HAZARDS SUBCOMMITTEE MEETING, FEBRUARY 1989.

4. F. L. BANTA, W. A. KENNEDY AND B. G. MORTON, "ELECTROSTATIC EFFECTS PROTECTIVE COATING FOR SOLID ROCKET MOTORS," PRESENTED AT THE JANNAF PROPULSION MEETING, AUGUST 1986.

The January 11, 1985 ESD initiated ignition of a Pershing II Stage I solid rocket motor prompted BMO (Ballistic Missile Office) to look at similarities between the Pershing II Stage I motor and the Peacekeeper Solid Rocket Motor Stages.

The similarities of the Pershing II Stage I propellant and the Kevlar motor cases caused BMO/TRW System Safety to initiate the Ballistic Missile Electrostatic Control Program.

BACKGROUND

- IN JANUARY 1985, A PERSHING II STAGE I SOLID ROCKET MOTOR IGNITED AND BURNED DUE TO AN ESD EVENT
- THE PERSHING MOTOR WAS COMPARED TO THE PEACEKEEPER SOLID ROCKET MOTORS FOR SIMILARITIES
- THE PEACEKEEPER STAGE I AND II WERE FOUND TO BE COMPATIBLE WITH THE PERSHING PROPELLANT AND KEVLAR MOTOR CASE
- SIMILARITIES BETWEEN THE TWO SYSTEM PROMPTED BMO TO INITIATE THE BALLISTIC MISSILE ELECTROSTATIC CONTROL PROGRAM.

The Ballistic Missile Control Program had three elements; problem identification, corrective actions and verification of the mitigation designs and procedures.

BALLISTIC MISSILE ELECTROSTATIC CONTROL PROGRAM

- o PROBLEM IDENTIFICATION
- o CORRECTIVE ACTION
- o VERIFICATION

To identify specific Peacekeeper concerns, tests and analyses were performed. These tests included measurements of charging processes both in the field and in the laboratory; computer modeling of the phenomena and material testing.

PROBLEM IDENTIFICATION

- o CHARGE GENERATION MEASUREMENTS
- o MATERIAL PROPERTIES MEASUREMENTS
- o PROPELLANT TESTING
- o EMPTY MOTOR TESTS
- o COMPUTER MODELING

The charge generation measurements were made during all phases of handling and transportation operations. The measurements were made by the contractors, Air Force personnel and TRW personnel. The results were compiled into a database (Electrostatic Effects Matrix) for later use. Excerpts are shown below.

The magnitude of the charges measured on the motor showed that a potential problem existed.

CHARGE GENERATION MEASUREMENTS

OPERATION	MEASURED SURFACE	% HUMIDITY	TEMP. (°F)	POTENTIAL (VOLTS)
LOADING INTO TRANSPORTER	FORWARD DOME	71	73	- 3500
MOVE VERTICAL TO HORIZONTAL ON INVERT FIXTURE	STAGE EPM	28	85	- 4000
MOVE FROM INVERT FIXTURE TO TRANSPORT TRAILER	STAGE EPM	24	78	-18000
REMOVE PLASTIC BOSS PROTECTOR FROM NOZZLE BOSS	PLASTIC PROTECTOR METAL BOSS	58 58	64 64	-10000 + 5000
LIFT-OFF OF LOW BOY CHOCKS ONTO TILT FIXTURE	SYNTHETIC ROPE ON LIFT BEAM	45	66	- 6000
ENVIRONMENTAL COVER	BLUE POLY, GENERAL COVER ON MOTOR	-- --	72-78 72-78	+16000 +10000
DRILLING HOLES IN MOTOR SKIRTS - APPLYING TAPE TO MOTOR	TAPE AND MOTOR	34	72-78	+ 5000

In order to make a proper assessment of the magnitude of the ESD hazard, it was necessary to know the material properties of the motor case materials. This data was also required for the modeling efforts.

The material properties of interest were the volume resistivity, surface resistivity and dielectric constants.

MATERIAL PROPERTIES MEASUREMENTS

SUMMARY OF MOTOR CASE MATERIAL PROPERTY MEASUREMENTS

MATERIAL	SURFACE RESISTIVITY (ohms/square)	VOLUME RESISTIVITY (ohms-cm)	DIELECTRIC CONSTANT	MEASURED BY
KEVLAR CASING (STAGE I)	1.5×10^{15}			TRW
KEVLAR CASING (STAGE II)	1.5×10^{12}			TRW
	4.9×10^{10}	8.9×10^{13}		APSC
KEVLAR CASING (STAGE III)	5.9×10^{13}			TRW
		1.0×10^{13}	- 6.0	HAD
EPDM	1.5×10^{16}	5.4×10^{14}		TRW
		3.7×10^{14}	3.1	HAD
	5.6×10^{15}	5.9×10^{15}		APSC
	6.0×10^{11}			MM
WEI	2.9×10^{12}	5.3×10^{14}		TRW
EPM	8.9×10^{12}	6.1×10^{11}		TRW
	1.1×10^{13}			APSC
	6.0×10^{9}		5.0	MM
		5.0×10^{11}		MTI

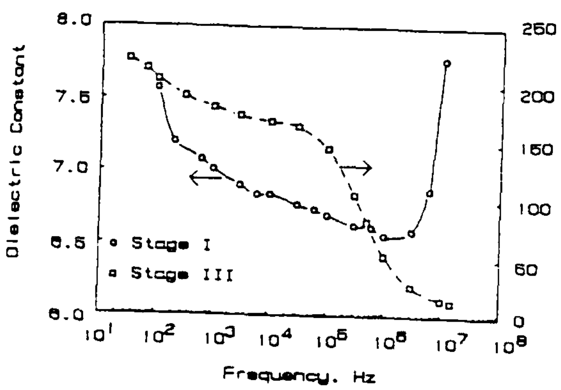
TRW TRW
APSC AEROJET STRATEGIC PROPULSION COMPANY
HAD HERCULES AEROSPACE DIVISION
MM MARTIN MARIETTA
MTI MORTON THIOKOL, INC.

The order to determine the criteria for propellant ESD ignition, Peacekeeper solid propellants were tested. The tests measured the electrical properties of the propellants. The volume resistivities as well as the dielectric constants were measured.

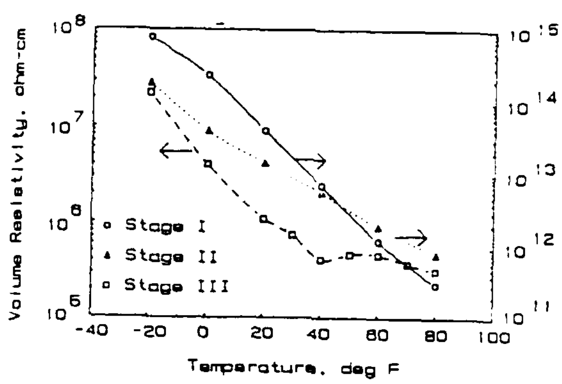
These electrical properties were also needed for the modeling.

PROPELLANT TESTING

ELECTRICAL PROPERTIES



DIELECTRIC CONSTANT

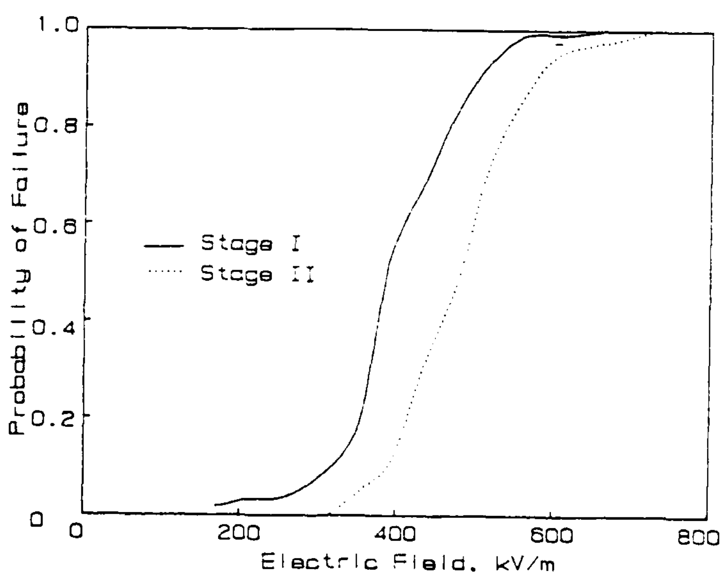


VOLUME RESISTIVITY

In addition to the electrical properties, voltage breakdown tests were conducted to determine the ESD sensitivity of the propellant. The breakdown tests were conducted by applying a potential by means of conductive plates attached to the top and bottom of the propellant samples (100 mm long by 90 mm in diameter). The applied potential was increased until an electrical breakdown occurred. The tests were performed at several temperatures. Statistical analysis was done on the data to produce a probability of ignition as a function of electric field across the propellant. These curves for Stage I and II propellants are shown below. Under the applied test conditions the Stage III propellant samples proved insensitive to ESD.

PROPELLANT TESTING

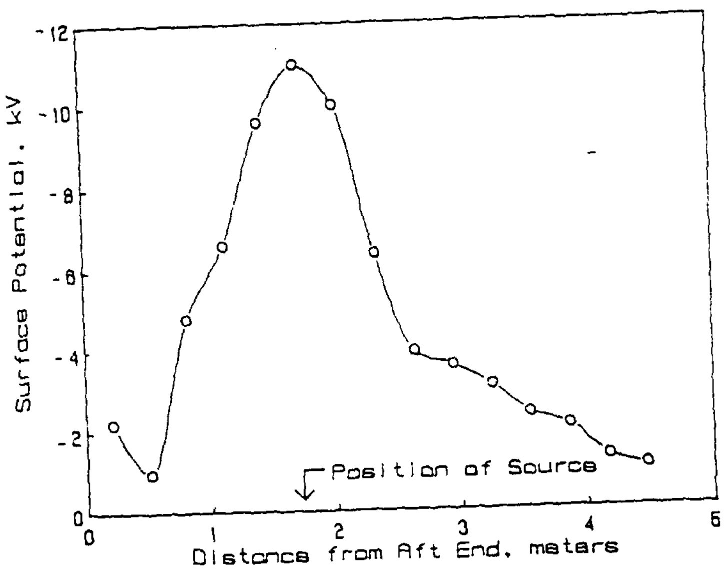
ESD SENSITIVITY



Empty motor case testing was performed to demonstrate that charge could be coupled through the insulating cases and to determine the magnitude of the potentials that would be produced on the propellant.

The motor case was excited by a DC high voltage steady-state source in a one foot square area. The interior and exterior potential distribution of the motor was then mapped. The results showed that large voltages (peak value approximately equal to applied potential) can be induced in the interior of the motor by charges on the exterior motor surfaces. The induced voltages were found to scale linearly with applied potential.

EMPTY MOTOR CASE TESTING



EXTERIOR OF MOTOR EXCITED WITH 10KV DC SOURCE

Testing of a full scale solid rocket motor like Peacekeeper for ESD ignition hazard was not considered practical. The only alternative for predicting the ESD threat is by modeling. The Peacekeeper Program supported two independent modeling efforts towards this end. The TRW modeling will be discussed here.

The TRW modeling effort was divided into two parts. The first part was to develop an ignition model for the propellant. The second part was to develop a circuit model representation of the solid rocket motor. The results of the two efforts were then combined determine the ESD hazard to the motor.

TRW COMPUTER MODELING

- o DEVELOP AN IGNITION MODEL FOR PROPELLANT
- o DEVELOP CIRCUIT MODEL REPRESENTATION OF SOLID ROCKET MOTOR
- o COMBINE EFFORTS TO DETERMINE ESD HAZARD

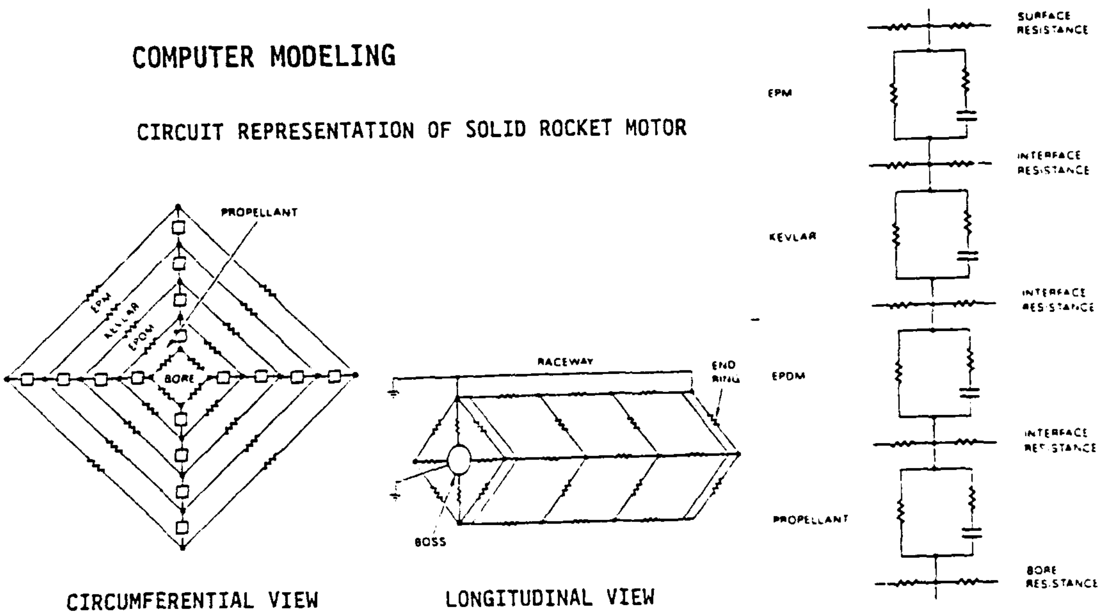
A solid phase thermal model was developed to obtain how much electrical energy would be required to ignite the propellant. The surface of the propellant was exposed to a constant rate of energy disposition. At rates below 1.3 kW/cm^2, the heat was conducted away with only a slight temperature increase with time. However, at rates above 1.3 kW/cm^2, it was apparent that in less than one millisecond the chemical self-heating predominates and thereby sustains the ignition event.

TRW COMPUTER MODELING

IGNITION MODEL

- o SOLID PHASE THERMAL MODEL DEVELOPED
- o ELECTRICAL ENERGY REQUIRED TO IGNITE PROPELLANT DETERMINED
- o IGNITION CRITERIA
  - ENERGY DEPOSITION OF 1.3 KW/CM^2
  - FOR > 1 MILLISECOND

A three-dimensional electrical circuit model of the model was formulated. The model is a lumped element model composed of resistors and capacitors. The model predicts the voltage/current distribution within the propellant produced by transients and steady-state potentials applied to the motor exterior.



CIRCUMFERENTIAL VIEW

LONGITUDINAL VIEW

CIRCUIT SEGMENT OF ANALYTICAL MODEL

This modeling demonstrated that two conditions are necessary for an ESD event to occur, energy storage resulting from large potentials being generated on the motor and propellant breakdown.

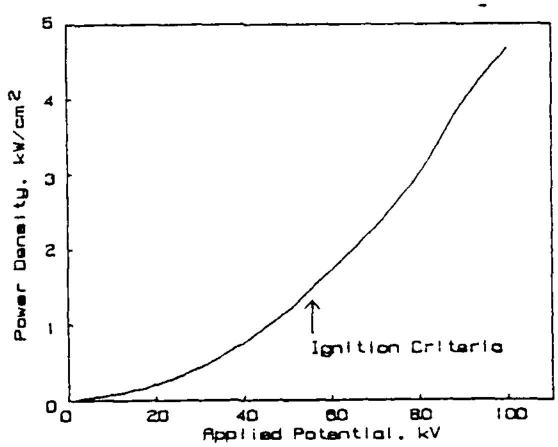
The model showed that if propellant breakdown occurred when the motor was charged greater than 56 kV, ignition could occur.

COMPUTER MODELING

IGNITION CRITERIA

- ENERGY STORAGE IN PROPELLANT FROM LARGE POTENTIALS GENERATED ON MOTOR

- PROPELLANT BREAKDOWN



The corrective actions were based on the results of the measurements and analyses performed. The goal is to: minimize charge generators by material selection and/or grounding practices; eliminate the risk of an ESD through procedural changes; protect the propellant from possible ignition caused by a discharge through the use of a DC Faraday cage; and increase ESD hazard awareness of the community through briefings and training films. These actions will ensure that the risk of ESD ignition of a Peacekeeper solid rocket motor is eliminated.

CORRECTIVE ACTIONS

GOALS

- o MINIMIZE CHARGE GENERATORS
  - -- MATERIAL SELECTION
  - -- GROUNDING PRACTICES
- o ELIMINATE RISK OF ESD THROUGH PROCEDURAL CHANGES
- o PROTECT PROPELLANT FROM ESD IGNITION
  - -- GROUNDED MOTOR CASE WILL NOT CHARGE UP
  - -- PREVENT POSSIBILITY OF PROPELLANT BREAKDOWN
- o INCREASED ESD HAZARD AWARENESS OF COMMUNITY

The primarily corrective action take was the development and implementation of a conductive coating for the solid rocket motors. The conductive coating has a surface resistivity of less than 10^6 ohms/square and once applied is grounded at all times. Additional actions include grounding of metallic hardware on the motors and the replacement of all surfaces in contact with the motor of transportation and handling equipment replaced with grounded conductive materials.

ESD mitigation requirements were written into the procedures for handling the motors.

To bring ESD awareness to the personnel involved in the handling of motors, all stage contractors developed and implemented ESD training courses. In addition, BMO developed a video tape explaining design modifications and the importance of adherence to the grounding procedures and handling precautions.

CORRECTIVE ACTIONS

- CONDUCTIVE COATING DEVELOPED AND IMPLEMENTED FOR THE SOLID ROCKET MOTOR STAGES
  - SURFACE RESISTIVITY $\leq 10^6$ OHMS/SQUARE
  - GROUNDED AT ALL TIMES
- MODIFICATION OF HANDLING AND TRANSPORTATION EQUIPMENT
  - ALL SURFACES IN CONTACT WITH MOTOR REPLACED WITH GROUNDED CONDUCTIVE MATERIALS
- MODIFICATION OF PROCEDURES TO MINIMIZE CHARGE GENERATION
- ESD AWARENESS
  - TRAINING COURSES DEVELOPED AND GIVEN TO ALL PERSONNEL HANDLING MOTORS
  - VIDEO TAPE DESCRIBING THE PROBLEM AND MITIGATION DEVELOPED BY BMO

Verification of the corrective actions was accomplished through tests, analysis and inspection.

VERIFICATION OF CORRECTIVE ACTIONS

- o EMPTY MOTOR CASE TESTING
- o SYSTEM SENSITIVITY ANALYSIS
- o AUDITS

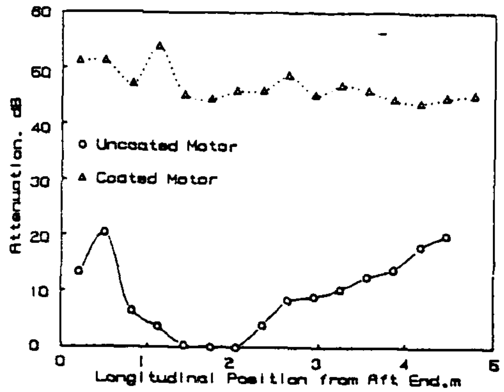
Extensive testing was done on the same Stage I motor used in previous tests to determine the effectiveness of the DC Faraday cage. A comparison of the interior potentials measured with and without the conductive coating is shown below. The DC attenuation measured was greater than 42 dB in the motor with the conductive coating (properly grounded) while at some locations zero attenuation was measured in the motor case without the conductive coating. The tests also demonstrated that without the proper grounding the conductive coating was not effective.

The attenuation is given by:

$$dB = 20 \log \frac{V_{source}}{V_{interior}}$$

VERIFICATION OF CORRECTIVE ACTIONS

EMPTY MOTOR CASE TESTING

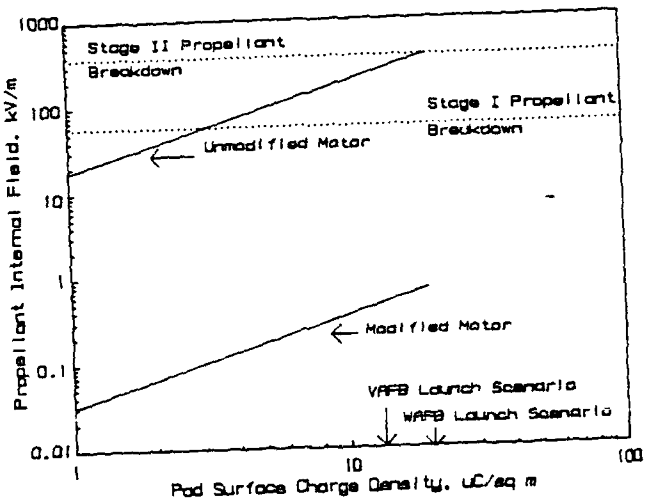


THE EMPTY MOTOR TEST DEMONSTRATES THAT THE CONDUCTIVE COATING IS AN EFFECTIVE MITIGATION DESIGN IF GROUNDED PROPERLY.

A system sensitivity analysis was performed. The analysis incorporated the results of charging measurements, modeling empty motor tests, and propellant testing. The system assessment showed that with the corrective actions implemented, the Peacekeeper solid rocket motors would be safe from ESD ignition.

VERIFICATION OF CORRECTIVE ACTIONS

SYSTEM SENSITIVITY ANALYSIS



THE ANALYSIS DEMONSTRATES THAT THE CORRECTIVE ACTIONS IMPLEMENTED ENSURE THAT THE PEACEKEEPER SOLID ROCKET MOTORS ARE SAFE FROM ESD IGNITION.

CONCLUSIONS

THE BALLISTIC MISSILE OFFICE HAS SPONSORED A LONG AND INTENSIVE EFFORT TO:

- o DETERMINE IF PEACEKEEPER SOLID ROCKET MOTORS WERE SUSCEPTIBLE TO ELECTROSTATIC IGNITION
- o DETERMINE WHAT CORRECTIVE ACTIONS WERE NECESSARY TO ENSURE SAFETY OF THE PEACEKEEPER SYSTEM
- o IMPLEMENT THOSE CORRECTIVE ACTIONS IN A TIMELY MANNER

THE EFFECTIVENESS OF THE CORRECTIVE ACTIONS HAS BEEN VERIFIED BY TESTS AND ANALYSIS. THE RESULTS OF THOSE EFFORTS SHOWED THAT WITH THE CORRECTIVE ACTIONS IMPLEMENTED, PEACEKEEPER SOLID ROCKET MOTORS ARE NOT SUSCEPTIBLE TO ELECTROSTATIC IGNITION.

A FRACTAL APPROACH TO MODELING ELECTROSTATIC DISCHARGE IN PROPELLANTS*

D. L. Shaeffer and J. E. Faulkner
Physics International Company
San Leandro, California

ABSTRACT

A deterministic fractal lattice (DFL) approach to modeling the electrical behavior of propellants has been investigated. This approach adopts an equivalent circuit model as a basic building block for a more complex model. The latter is formed by continuously subdividing the heterogenous material in a way that preserves self-similarity of the material and the equivalent circuit model. This approach permits a completely analytic solution for the complex impedance of the propellant in terms of an exact renormalization, T(x), *of the normalized complex frequency.* This approach allows an analytic determination of the transient response of the propellant to an arbitrary applied time-dependent voltage waveform. In addition, a multiplicity of time constants is given by the solution. These time constants are related to the Julia set of the transformation, T. The probability density function and the cumulative probability function of the time constants are derived. The latter is shown to be the Devil's staircase, well-known from fractal theory. The relationship of this approach to percolation theory is demonstrated. The model is developed for two dimensions as well as three dimensions. The model is also extended to permit multiple types of particulates and to allow for occurrence of a battery effect. This approach has the advantage of permitting inclusion of microphysics and yet remaining mathematically tractable.

A Fractal Approach to Modeling ESD in Propellants

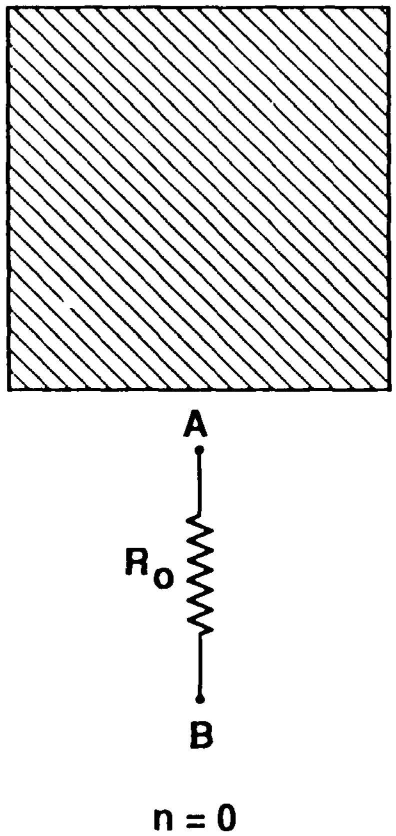
by

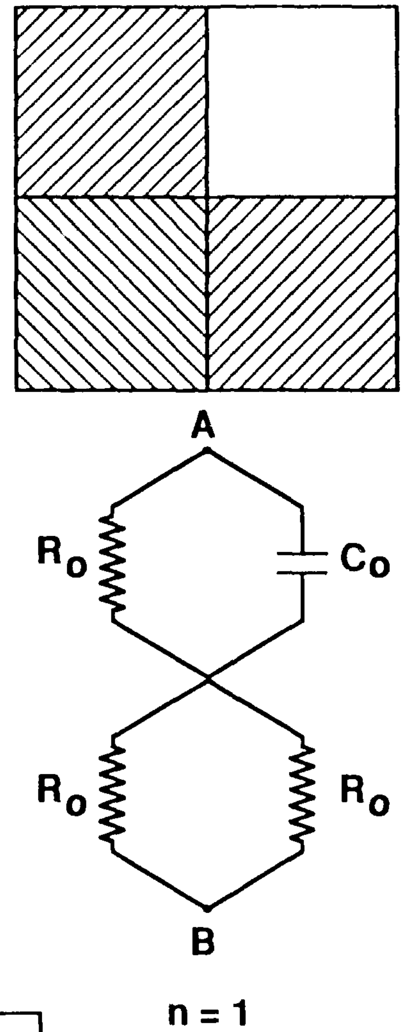
D. Lynn Shaeffer
and
James E. Faulkner
Physics International
San Leandro, CA

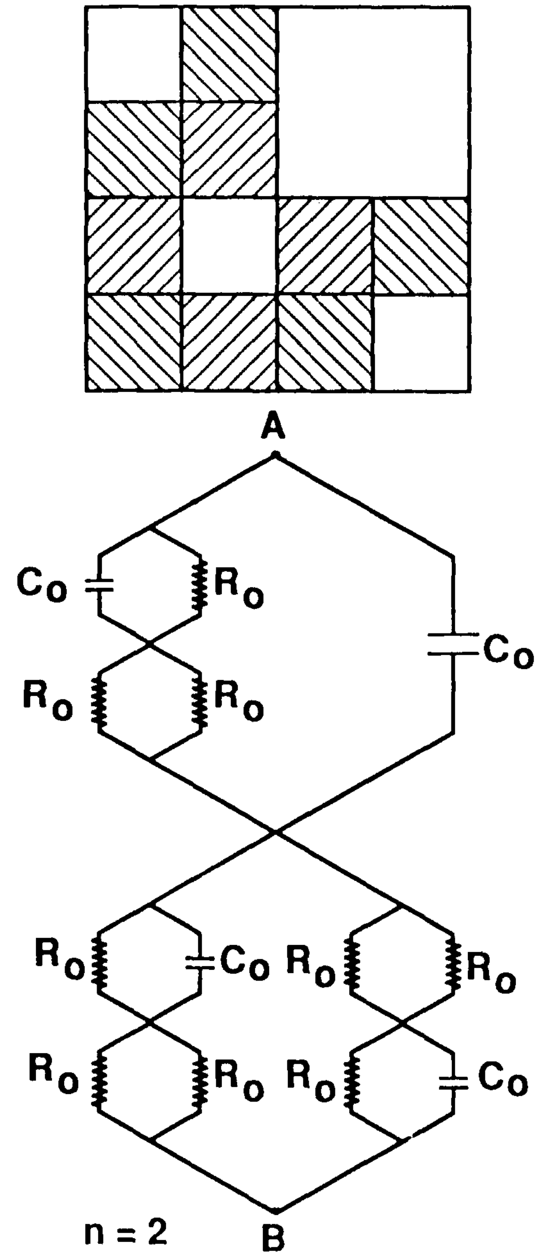
Presented at
1989 JANNAF PSH Subcommittee Meeting
San Antonio, Texas

24 February, 1989

2D Deterministic Fractal Lattice (DFL)







$f = 3/4$

$$d_f = \frac{\log 3}{\log 2} = 1.585$$

MS07.1

FREQUENCY-DEPENDENT IMPEDANCE

$$Z_n(\omega) = \frac{1}{2} Z_{n-1}(\omega) + \left[\frac{4(1-f)}{\eta(\omega)} + \frac{4f-2}{Z_{n-1}(\omega)} \right]^{-1}$$

$$\eta(\omega) = \frac{1}{j\omega C_0}$$

$$Z_0 = R_0$$

$$Z_n(\omega) = \frac{1}{j\omega C_0} T^n\left(\frac{j\omega}{\omega_0}\right)$$

$$\omega_0 = \frac{1}{R_0 C_0}$$

$$T^n = T \circ T \circ T \circ \ldots, T \quad , n \text{ times}$$

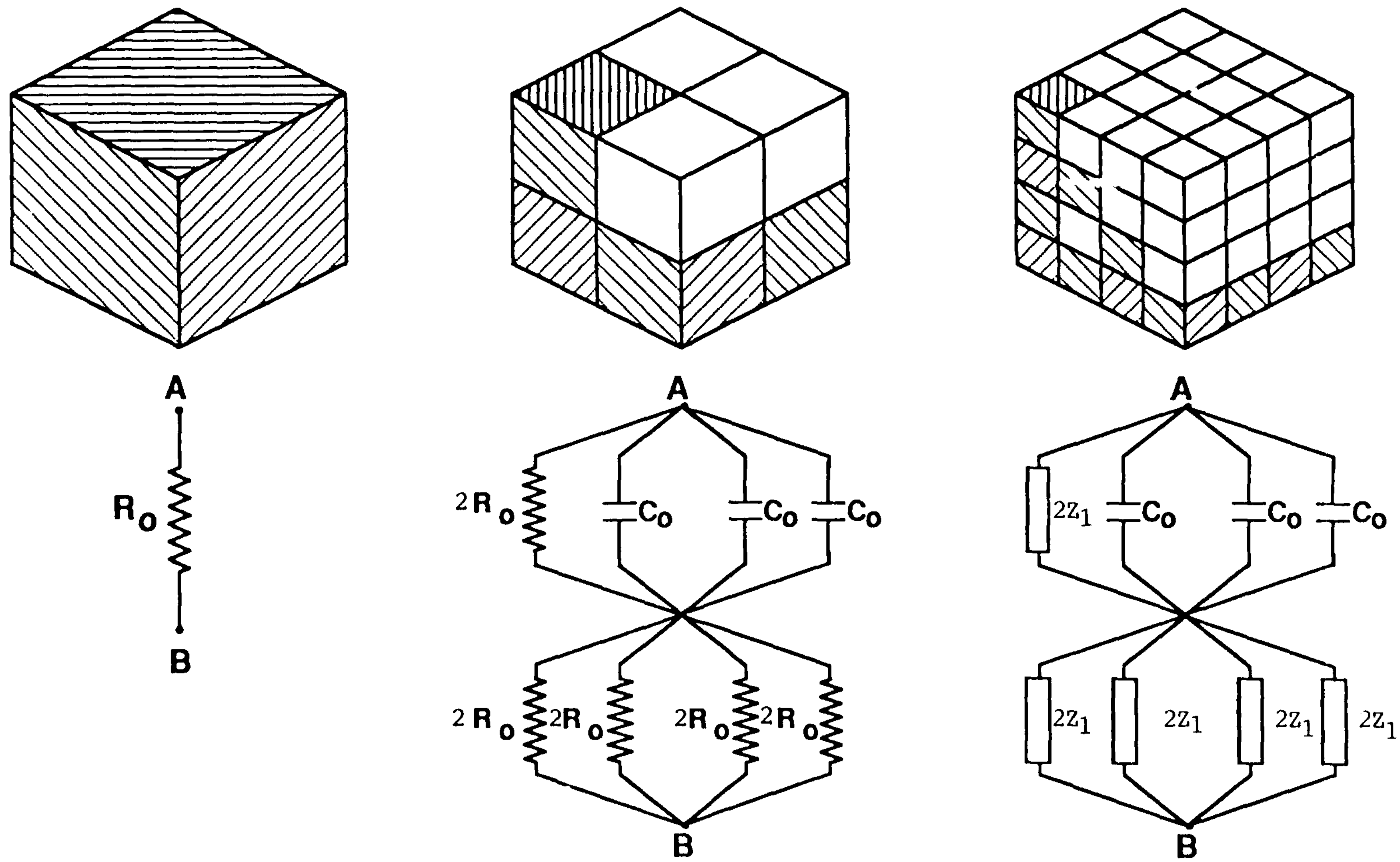
$$T(x) = x \, \frac{(1-f)x + f}{2(1-f)x + 2f - 1}$$

$T^n(x)$ CONTAINS THE SECRETS OF THE ELECTRICAL PROPERTIES OF THE LATTICE

3D DFL Model

f = 5/8

$$d_f = \frac{\log 5}{\log 2} = 2.322$$



n = 0 n = 1 n = 2

Olin
MS07.1

3-D IMPEDANCE

$$Z_n(\omega) = \frac{1}{4} Z_{n-1}(\omega) + \left[\frac{8(1-f)}{\eta(\omega)} + \frac{8f-4}{Z_{n-1}(\omega)} \right]^{-1}$$

$$\eta(\omega) = \frac{1}{j\omega C_0}$$

$$2^{-n} \mathfrak{z}_n(\omega) = Z_n(\omega)$$

$$\mathfrak{z}_n(\omega) = \frac{1}{j\omega C_0} T^n \left(\frac{j\omega}{\omega_0} \right)$$

DC CASE

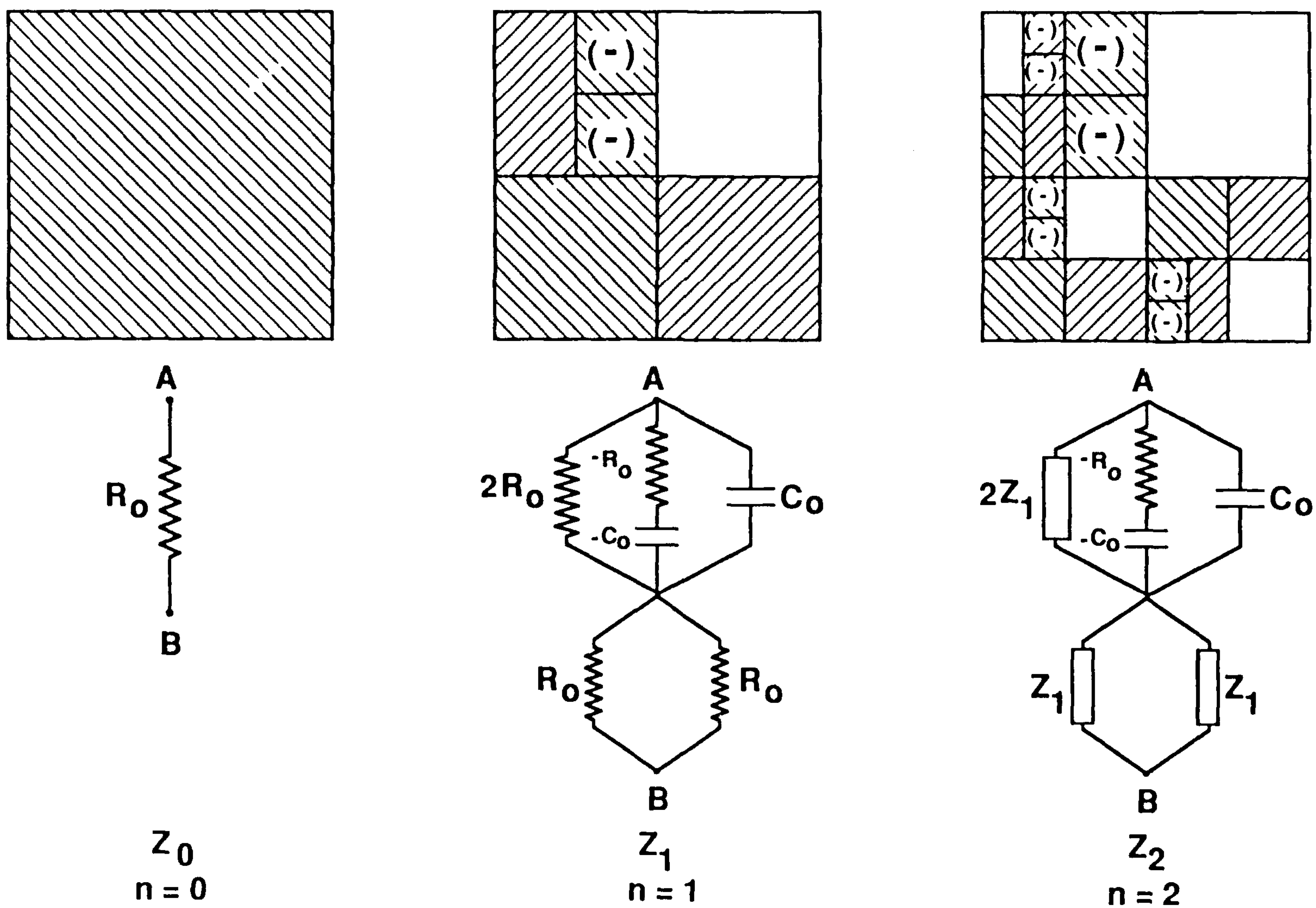
$$\rho = \mathfrak{z}_n(0)$$

$$\rho = R_0 L^{t/\nu}$$

2D DFL With Batteries

f = 3/4, Q = 1/2, g = 1/2

$$d_f = \frac{\log[2 + (4f - 2)\,Q(1+g)]}{\log 2} = 1.460$$



Olin MS07.1

FRACTALIZATION OF DOUBLE BASE PROPELLANT

FROM J. SMITH'S DATA:

$C_0 \approx 1.85 \times 10^{-11}$ F (ASSUMING $\epsilon_r = 5$)

$R_0 \approx 7.27 \times 10^{6}\ \Omega$ (FROM PRONY FIT TO 6.32 V DATA)

$R_0 C_0 \approx 1.34 \times 10^{-4}$ sec

DOMINANT TIME CONSTANT IN PRONY FIT TO 6.32V DATA WAS 12.5 sec

FRACTALIZATION ($n = 15$) $\Rightarrow$ # OF τ's = 65,536 (INCLUDING D.C. COMPONENT, i.e., $\tau_1 = 0$)

$$\tau_i = -\frac{R_0 C_0}{X_i}$$

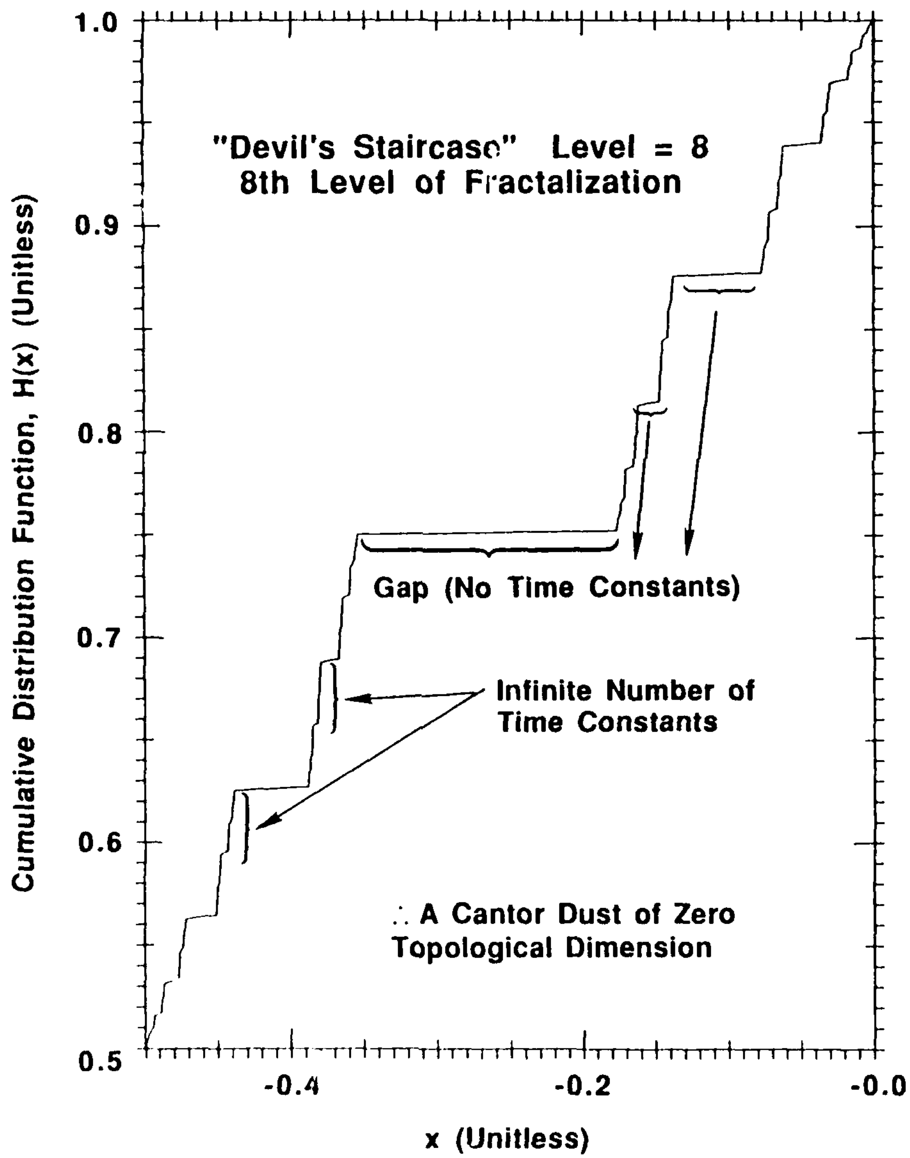
$\tau_s \simeq 10^{-9}$ sec

$\tau_\ell \simeq 10$ sec

ROUGH LINEAR DIMENSION, L_D, OF SMALLEST CELL

$$L_D \approx \frac{V^{1/3}}{2^{15}} \approx 0.1\,\mu = 10^{3}\ \text{Å}$$

Cumulative Distribution Function of Relaxation Times



Olin
MS07.1

EFFECTIVE DIELECTRIC CONSTANT OF DFL

$$I(t) = \epsilon^{*} C_v \dot{V}$$

$$I(\omega) = j\omega(\epsilon' - j\epsilon'')\, C_v\, V(\omega)$$

$$I_n(\omega) = V(\omega)/Z_n(\omega)$$

$$Z_n(\omega) = (j\omega C_0)^{-1}\, T^n\left(\frac{j\omega}{\omega_0}\right)$$

$$V(\omega)/Z(\omega) = j\omega(\epsilon' - j\epsilon'')\, V(\omega)\, C_v$$

$$\epsilon' - j\epsilon'' = \left[j\omega C_v Z_n(\omega)\right]^{-1}$$

$$\boxed{\epsilon' - j\epsilon'' = \frac{C_0}{C_v T^n\left(\frac{j\omega}{\omega_0}\right)}}$$

ASYMPTOTIC FORMS OF ϵ^* AND RELATION TO ϵ^* FOR M-W MODEL

$\underline{\omega \to 0}$

$$\epsilon' = \frac{c_0}{f C_v}\left[1 - \left(\frac{2f-1}{f}\right)^n\right]$$

$$\epsilon'' = \frac{\omega_0}{\omega}\left(\frac{2f-1}{f}\right)^n \frac{c_0}{C_v}$$

$\underline{\omega \to \infty}$

$$\epsilon' = \frac{2^{n-1}(2^n-1)\omega_0^2}{(1-f)\omega^2} \frac{c_0}{C_v}$$

$$\epsilon'' = \frac{2^n \omega_0}{\omega} \frac{c_0}{C_v}$$

PROPELLANT CHARACTERISTIC TIME CONSTANTS

BERGER et al. (HERCULES)

$$x' = x''$$

$$\Downarrow$$

$$f_c \sim \frac{1}{\tau_c}$$

τ_c IS A MEASURE OF ESD SENSITIVITY

DFL MODEL

MULTIPLICITY OF TIME CONSTANTS

USE τ_ℓ AS A MEASURE OF SENSITIVITY

P.S. - NEED TO MEASURE ϵ^* TO LOWER f'_ℓ.

Relationship Between 2D DFL Model Parameters and Experimental Data

Quantity	Relation for Calculation	Comments
$Z_n(\omega=0)$	$Z_n(0) = R_V(t=\infty)$	Equilibrium resistance determined from Prony fit to volume resistivity time domain data.
R_o	$R_o = R_b$	Resistance of equivalent volume of binder.
f		Determined from physical composition of propellant.
n	$n = \dfrac{R_V(\infty)}{R_b \ln\left(\frac{f}{2f-1}\right)}$	Fractal generation level
d_f	$d_f = \ln(4f)/\ln 2$	Fractal dimension (2D model)
τ_l	Taken as largest time constant of Prony fit to current, I(t), from step function response, or, $\tau_l = -R_oC_o/X_n$	
C_o	$C_o = -X_n\tau_l/R_o$, or	
	$C_o \approx fC_V\epsilon'(o)$	For large n
Xn	$X_n = T^n(X_n)$	
ω_o	$\omega_o = (R_oC_o)^{-1}$	
$\epsilon'-j\epsilon''$	$\epsilon'-j\epsilon'' = \dfrac{C_o}{C_V}\dfrac{1}{T^n\left(\frac{j\omega}{\omega_o}\right)}$	Also measured
t/V	$L^{t/V} = C_l(f)\omega_o\tau_l$, $L = 2^n$	$C_l(f)$ determined from a special function $F_o(x)$

Olin

CONCLUSIONS

- Deterministic Fractal Lattice (DFL):
- Provides analytic method for analyzing electrical properties of propellants
- Provides physical insight
- Explains multiplicity of time constants
- Provides a means of including microphysics and yet remaining tractable
- Has flexibility to allow altering of basic building block (i.e., equivalent circuit)
- Can be formulated and remain tractable in 3-D
- Relates electrical properties to percolation theory
- Predictions give reasonable results

Electric field in a concentrated dispersion of spheres

I. L. Davis, M. Salita, R. L. Hatch
Morton Thiokol, Inc., P. O. Box 524, Brigham City, Utah 84302

A solution technique is presented which calculates the static electric field at any point in a concentrated random dispersion of spherical particles when a uniform external electric field is applied across the dispersion. The particles may be of arbitrary size, position, and material composition. Using an iterative technique, the electric field may be calculated at any point in the medium or at any point inside a particle. The algorithm assumes all component materials are electrically isotropic and homogeneous and that the net charge on each particle is zero. This work is a first step in gaining a more fundamental understanding of electrostatic discharge phenomena through particulate-filled systems using recently-gained abilities to more accurately simulate the microstructure.

MICROSTRUCTURAL ESD:

ELECTRIC FIELD IN A CONCENTRATED DISPERSION OF SPHERES

I. Lee Davis
Robert L. Hatch
Mark Salita
Morton Thiokol, Inc.
Brigham City, Utah

Microstructure vs. Empiricism

The times - they are a' changin'

Complex Systems

Too many variables for empiricism.

Never has worked - never will.

Computational Physics

Must have:

(1) Knowledge of microstructure

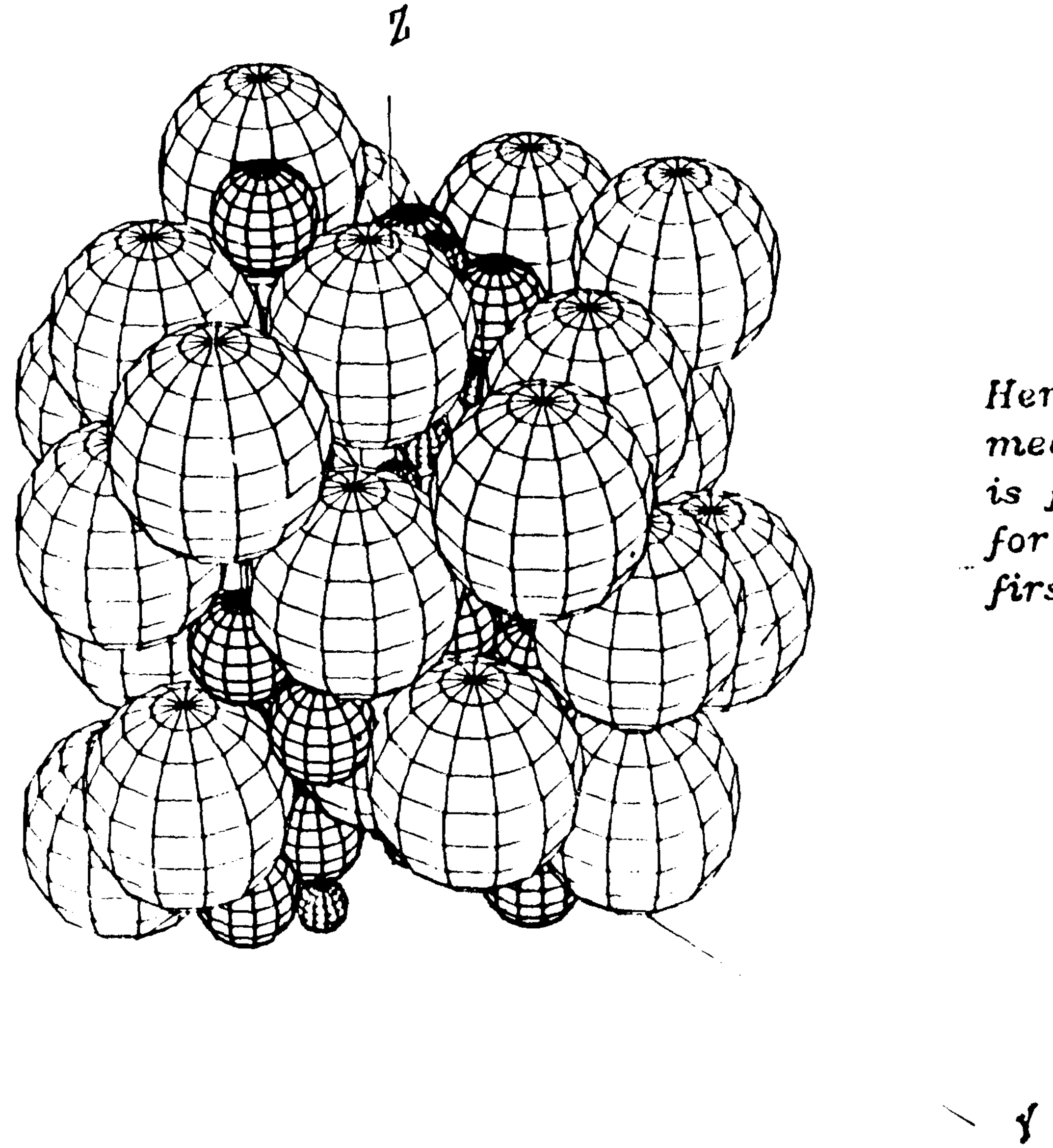
(2) Knowledge of first principles

(3) Fast computers

The Key: Simulating Random Particle Packs

Electric breakdown is driven by particle pack.

Ability to simulate random packs recently achieved for the first time through a dimension-reducing trick.



Hence, ESD mechanisms is feasible for the first time.

Objective

OVERALL

Use recently gained microstructural knowledge to predict ESD susceptibility of any propellant ***from first principles.***

THIS YEAR'S

Calculate electric field concentrations in a concentrated particle pack.

The Overall ESD Mechanisms Program

THE STATIC PROBLEM
- E field due to spheres
- E field due to ellipsoids
- E field due to irregular particles

THE DYNAMIC PROBLEM
- Microbreakdowns
- Macrobreakdowns
- Energy deposition and ignition

APPLICATIONS
- Reducing ESD sensitivity in current propellants
- Designing insensitive new propellants

Calculating Electric Field Concentrations

Cannot touch the problem numerically (FD or FE).

- *Can do only a few spheres - not thousands.*

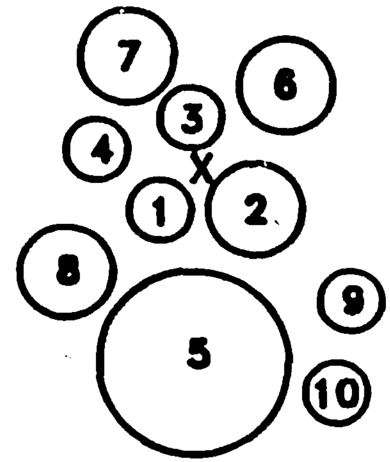
Powerful mathematical tool called orthogonal expansions.

- *Makes impossible problems hard and hard problems easy.*

Solve iteratively using spherical harmonics.

- *Computer keeps track of thousands of coefficients.*
- *Can do thousands of spheres to any accuracy.*

Solution Procedure

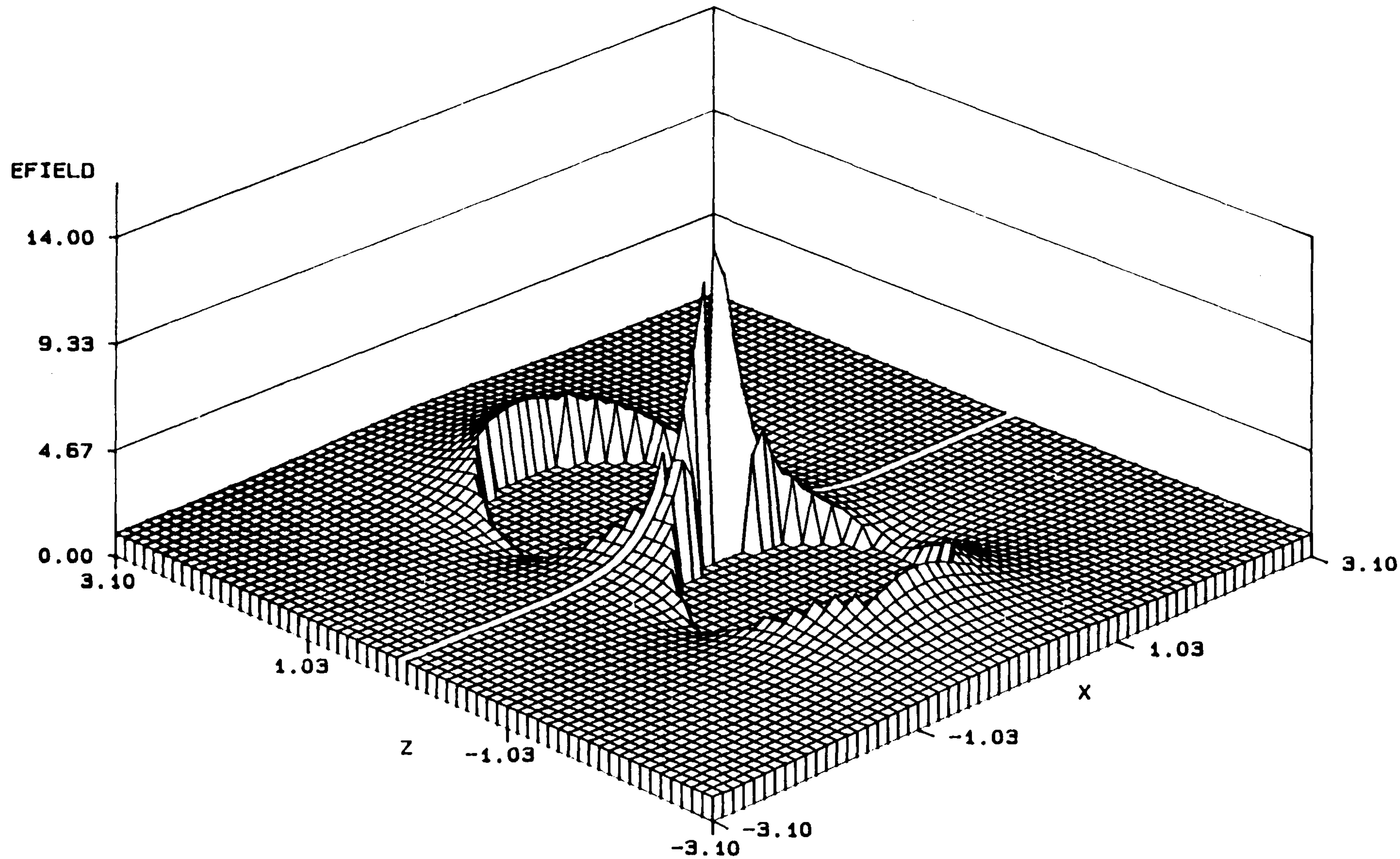


Pick point in the pack.
Determine active spheres.
Make initial solution guess.
Cycle through active spheres.

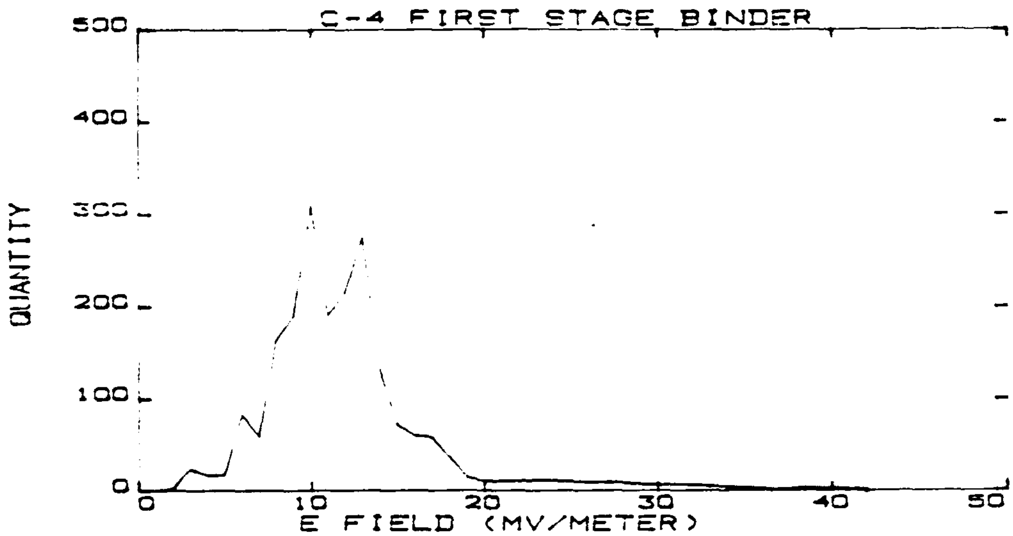
Add harmonic solutions to account for neighbor interactions.
Repeat until convergence.

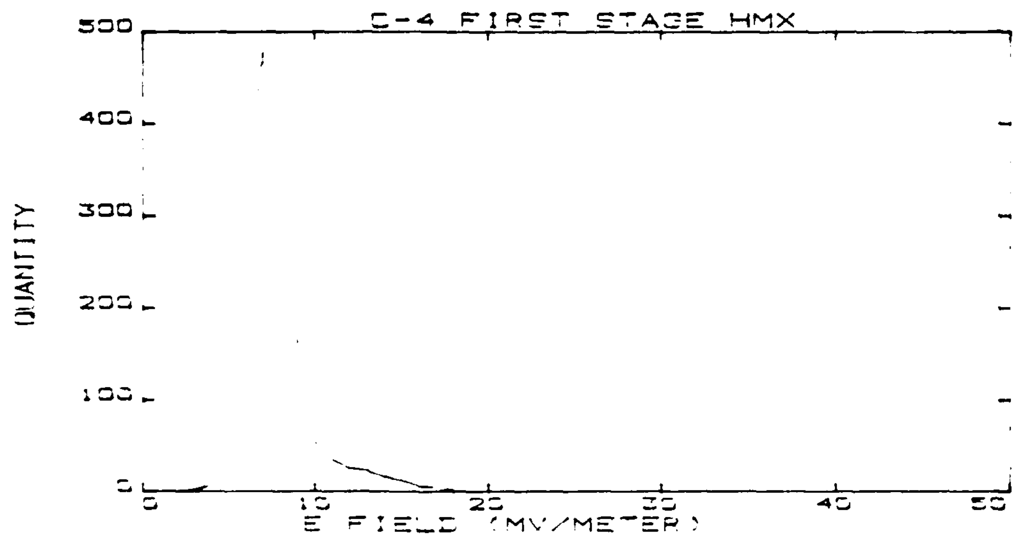
Output E field.
Go on to next point in the pack.

ELECTRIC FIELD CONCENTRATION
2 CONDUCTING SPHERES SEPARATED BY 1.05 RADII



E Field Concentrations





Dielectric constants: Binder (2), HMX (4), AP (6)

MICROSTRUCTURAL ESD: CONCLUSIONS

Have ability to simulate the microstructure.

Have completed the static problem. It works!

Need to proceed with dynamic and ignition problem.

MECHANISMS IS POSSIBLE.

We need to pursue it.

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EVALUATION OF PROPELLANT HAZARDS USING HIGH FREQUENCY ELECTRICAL PROPERTY MEASUREMENTS

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Hercules Incorporated, Allegany Ballistics Laboratory
Rocket Center, West Virginia

ABSTRACT

There is presently considerable interest in the measurement of the electrical properties of solid rocket propellants as a means of predicting their sensitivity to electrostatic phenomena. The electrical properties are found to vary with frequency, and their behavior in the high frequency regime may be an indicator of a material's susceptibility to potentially damaging electrostatic events.

Propellant dielectric constant, loss index, and AC volume resistivity have been determined from impedance measurements at frequencies between 1 MHz and 1 GHz. The dielectric constant decreased with increasing frequency for each sample tested. The rate of decrease varied considerably depending on the type of binder; HTPB propellants exhibited a change of about 8 percent between the lowest and highest frequency of the study, whereas CMDB propellants decreased 40 percent and CTPB propellants decreased about 3 percent. The AC volume resistivity decreased with increasing frequency for each sample. CMDB propellants are somewhat conductive even at the low frequencies. Both HTPB and CTPB propellants have a relatively high resistivity with the CTPB type slightly less conductive.

Loss index increased for all propellants, reaching a maximum at around 150 to 250 MHz and then decreased slightly at higher frequencies. The loss index of the CTPB propellants is 3 to 4 times lower than that of HTPB propellants. This indicates that more energy is dissipated in the form of heat in the HTPB propellants than in the CTPB samples.

HERCULES

EVALUATION OF PROPELLANT HAZARDS USING HIGH FREQUENCY ELECTRICAL PROPERTY MEASUREMENTS

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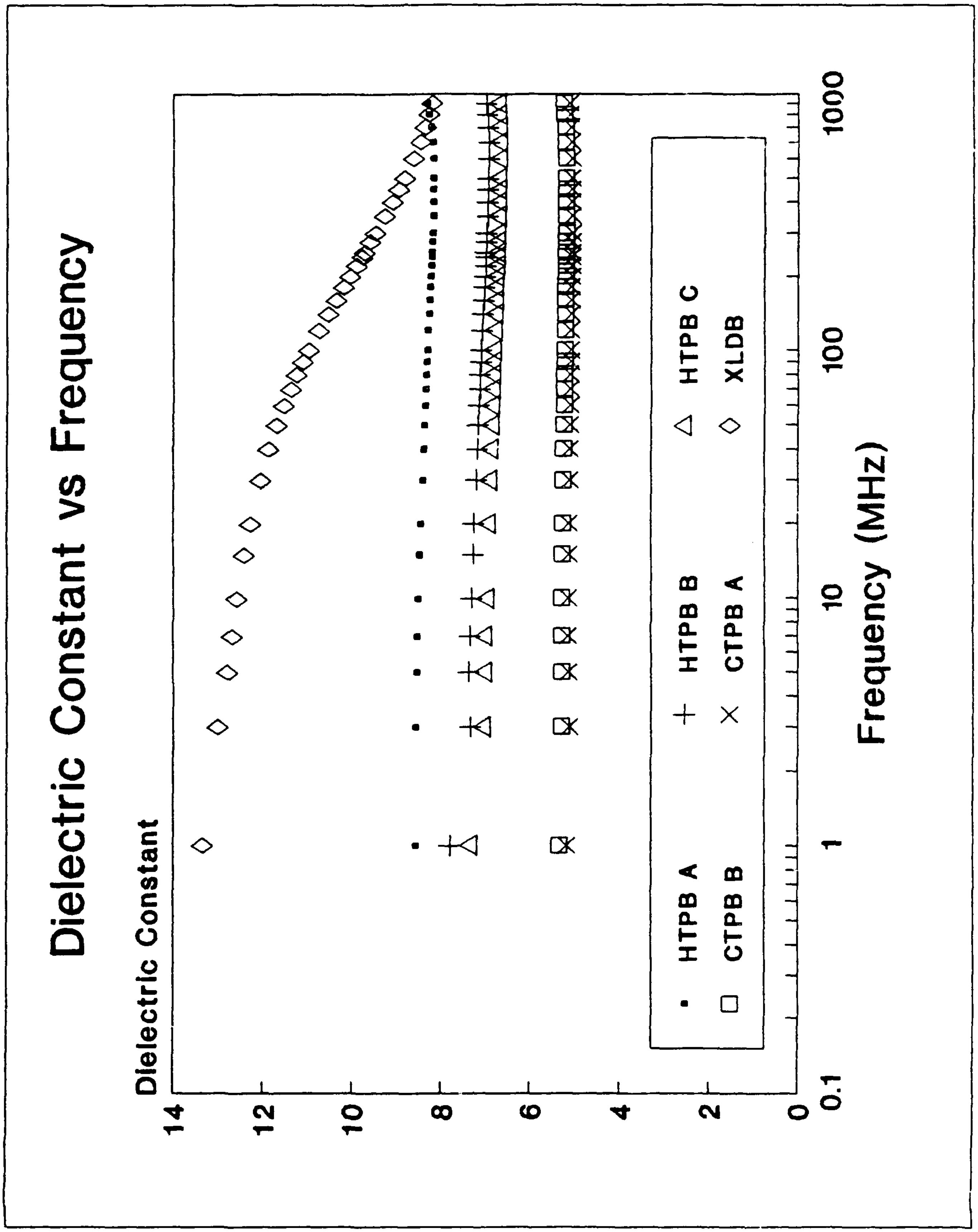
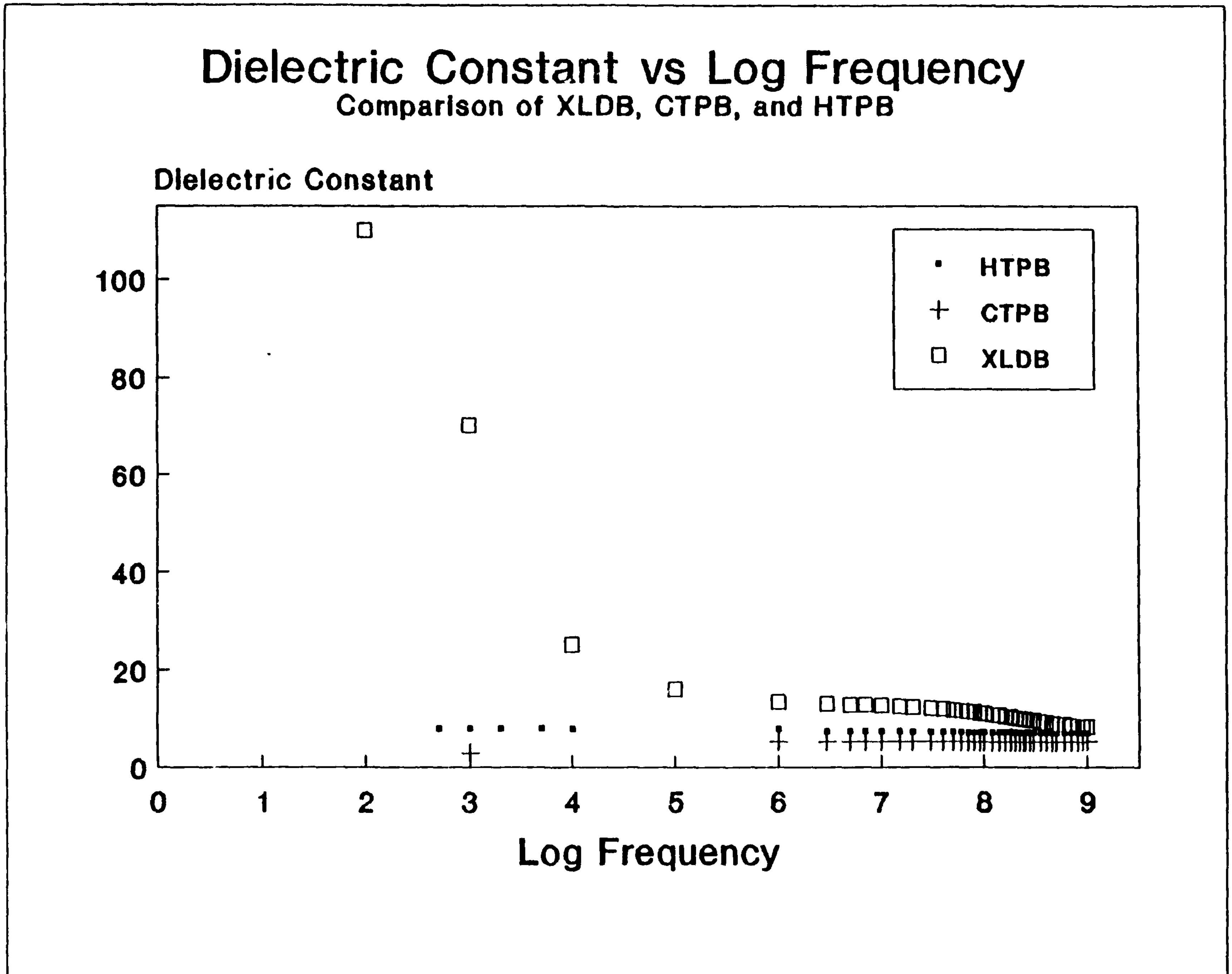
ALLEGANY BALLISTICS LABORATORY
ROCKET CENTER WV

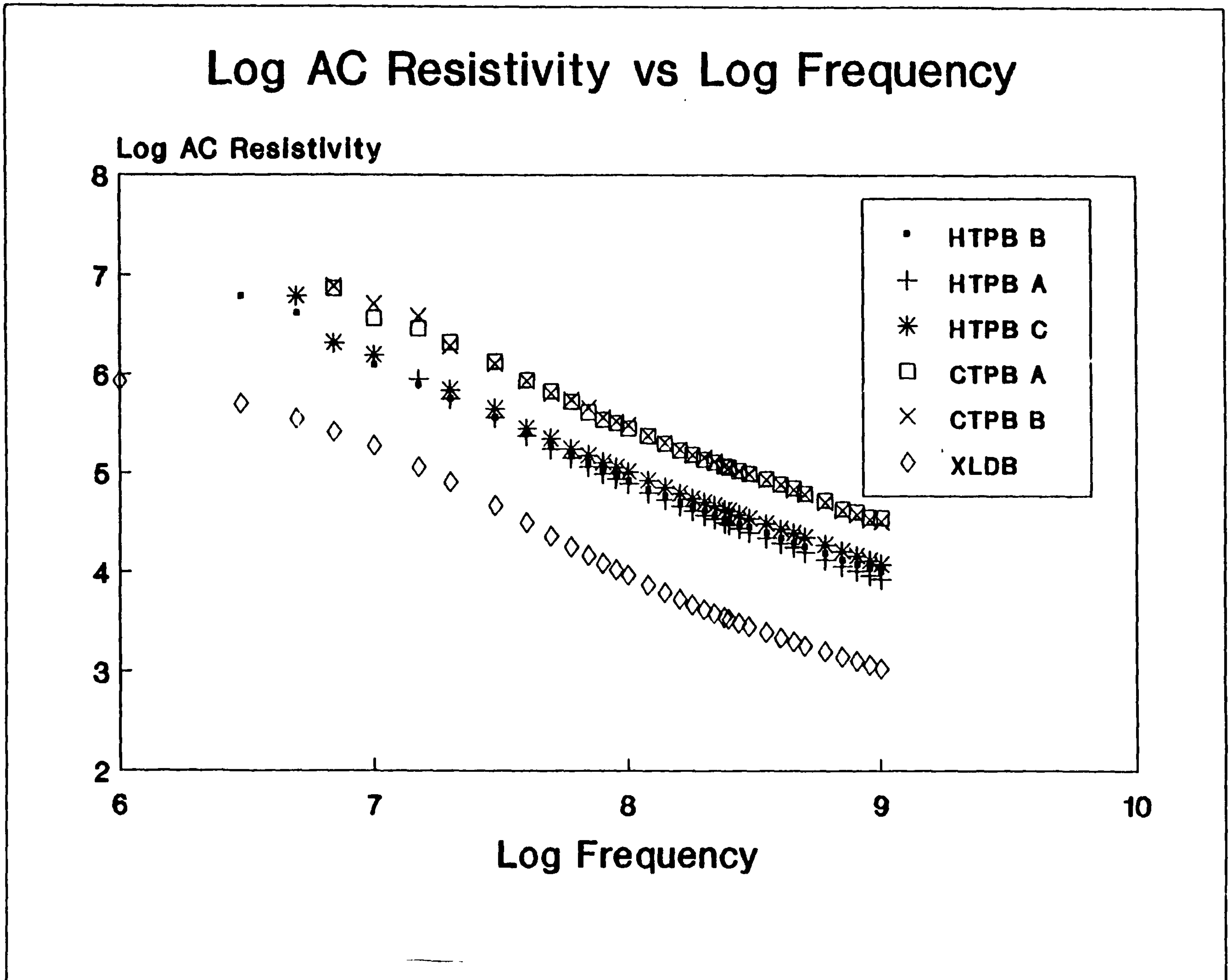
Objectives

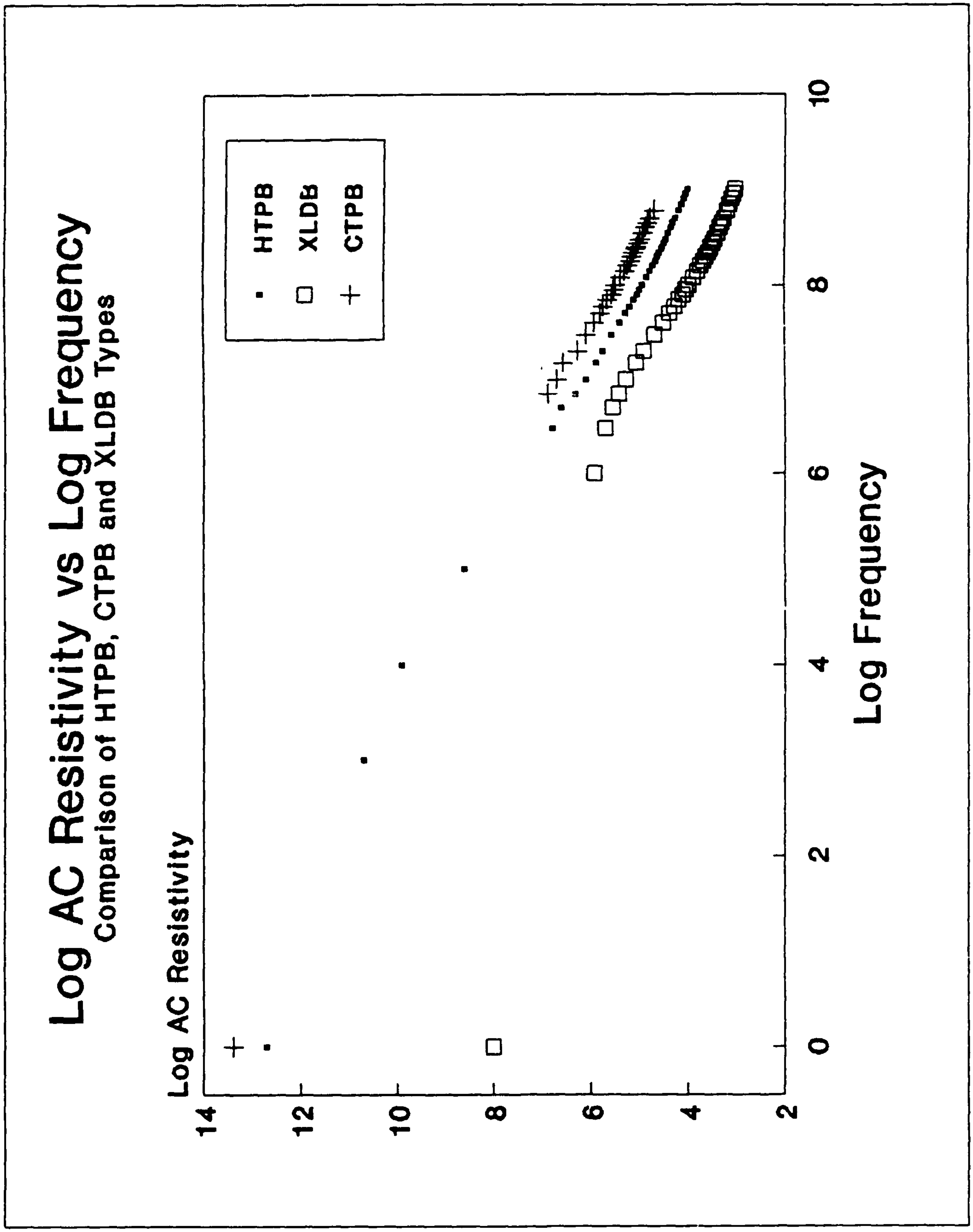
- Develop Measurement Techniques < 1E-6 Sec
- Examine Electrical Properties
  - a) Dielectric Constant
  - b) ac Volume Resistivity
  - c) Loss Index
- Identify Compositional Factors Which Alter Propellant Electrical Properties

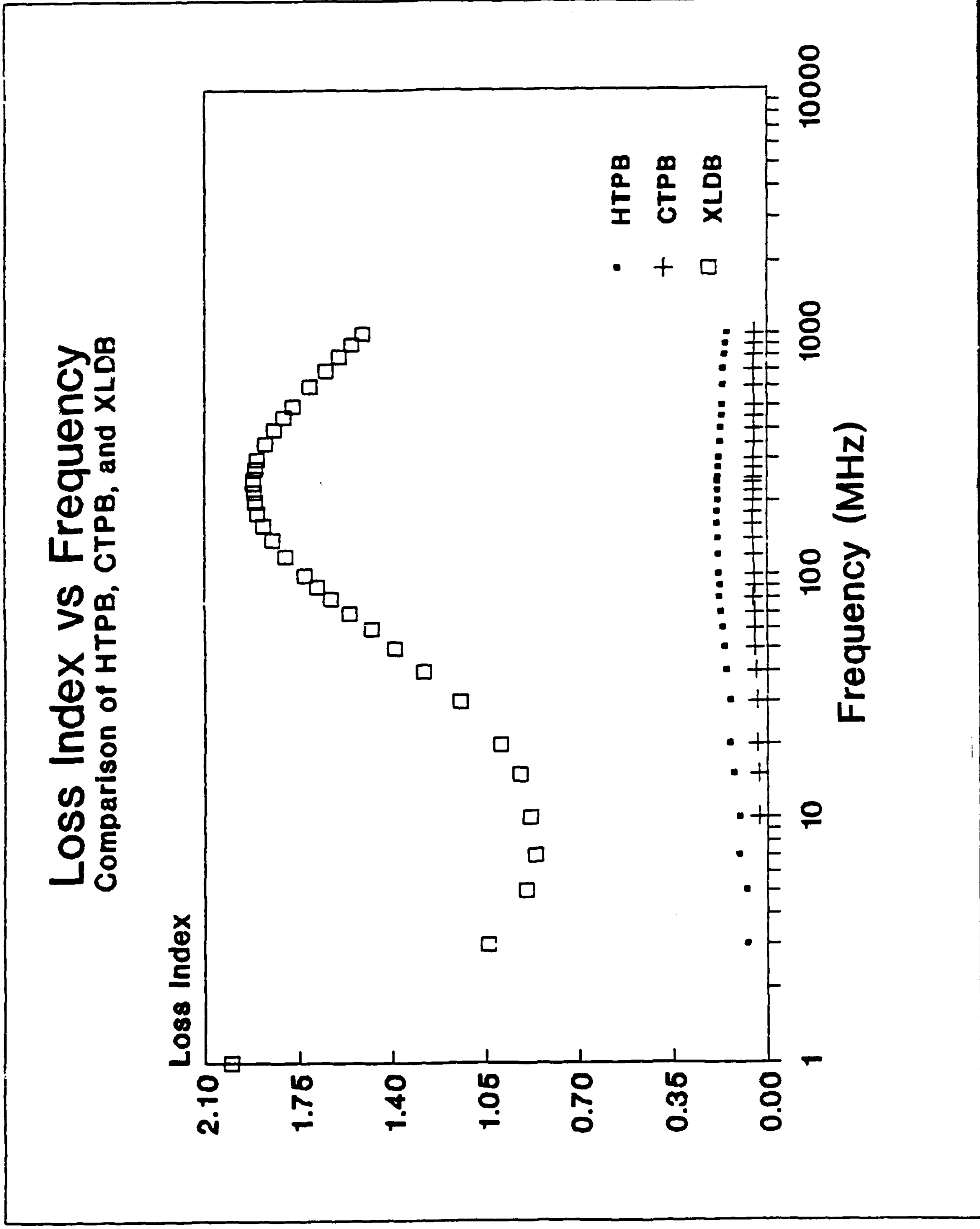

Dielectric Constant vs Frequency
Dielectric Constant
14
12
10
8
6
4
2
0
0.1
1
10
100
1000
Frequency (MHz)
HTPB A
HTPB B
HTPB C
CTPB B
CTPB A
XLDB



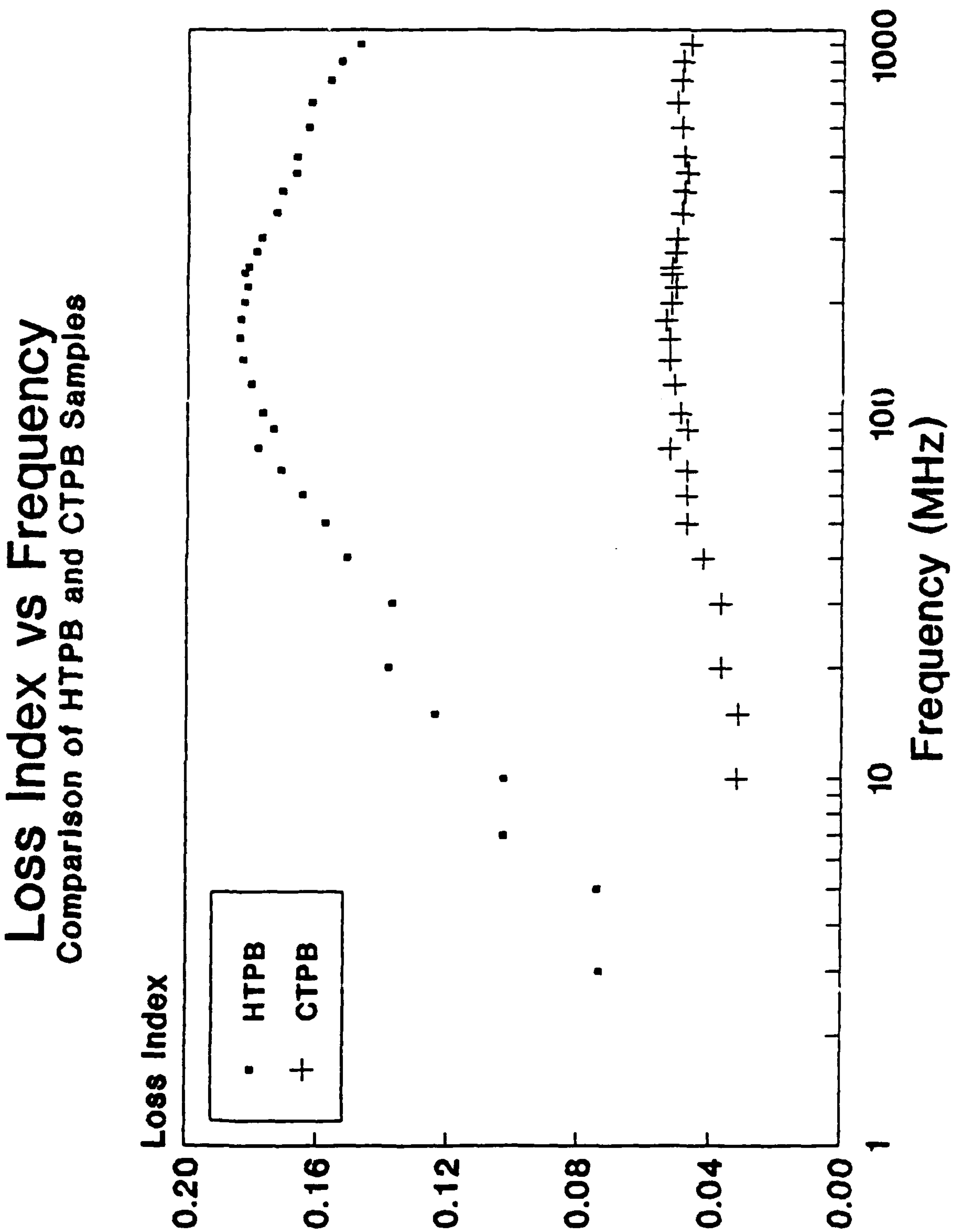
Dielectric Constant vs Log Frequency
Comparison of XLDB, CTPB, and HTPB
Dielectric Constant
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
Log Frequency
HTPB
CTPB
XLDB


Log AC Resistivity vs Log Frequency
Log AC Resistivity
8
7
6
5
4
3
2
6
7
8
9
10
Log Frequency
HTPB B
HTPB A
HTPB C
CTPB A
CTPB B
XLDB


Log AC Resistivity vs Log Frequency
Comparison of HTPB, CTPB and XLDB Types
Log AC Resistivity
14
12
10
8
6
4
2
0
2
4
6
8
10
Log Frequency
HTPB
XLDB
CTPB



Loss Index vs Frequency
Comparison of HTPB, CTPB, and XLDB
Loss Index
2.10
1.75
1.40
1.05
0.70
0.35
0.00
1
10
100
1000
10000
Frequency (MHz)
HTPB
CTPB
XLDB


Loss Index vs Frequency
Comparison of HTPB and CTPB Samples
Loss Index
0.20
0.16
0.12
0.08
0.04
0.00
1
10
100
1000
Frequency (MHz)
HTPB
CTPB

Conclusions

- Resistivity Decreases With Increasing Frequency For All Samples
- Variation of Properties is Most Significant For XLDB Propellants
- XLDB Has Highest Loss Index
- HTPB Propellants Are More "Lossy" Than CTPB Propellants
- Loss Index Tends to Peak at 100 MHz

Conclusions

- Variation of AP Size Has No Significant Effect
- Change of Spherical Aluminum Size From 7 to 28 Microns Has No Discernible Effect
- Change of Spherical Aluminum Concentration From 8 to 21 Percent By Weight Has Little Effect
- Flake Aluminum Has a Profound Effect

Conduction in An Aluminized Explosive During ESD

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Silver Spring, Maryland 20903-5000

A capacitive discharge circuit was used to measure electrical energy deposition in PBXW-115, an aluminized explosive. The circuit used two capacitances (54 µF and 0.4 µF) and voltages from 5 KV to 9 KV to vary the energy. It was observed that energies around 5 Joules were necessary before arc discharge could be initiated. Experiments with variations in electrode active area demonstrated that the pre-breakdown conduction was not localized. X-Ray Photoelectric Spectroscopy, XPS, studies were used to determine the degree of reaction for samples subjected to various energy depositions (3 to 150 Joules). The results indicate that the ignition energy is deposited during the arc discharge and not prior to breakdown as previously thought.

A reasonable comparison was made between NSWC's ESD ignition results (150 joules, 1 mm arc diameter) and Energy Fluence data from deflagration to detonation transition, DDT, studies.[1] Therefore, ESD ignition is likely dependent on the thermal ignition of a minimum volume. The arc discharge starts out highly localized (10^{-3} mm^2) and grows with increasing energy deposition. Studying this relationship between arc discharge diameter and energy deposition may provide a prediction of ignition sensitivity.

Drabkina[2] has provided an expression for the arc channel radius as a function of energy and deposition time. Mel'nikov and Nikitin[3] have solved the heat equation using this expression for radius to determine the activation energy, E, and the product of heat of reaction and the frequency factor, Qk_o. Future work will be aimed at using these techniques to predict ESD sensitivity for different naval explosives.

REFERENCES

1. Liddiard, T.P. and Forbes, J.W., A Summary Report of the Modified Gap Test and the Underwater Sensitivity Test, NSWC TR 86-350, March 12, (1987).

3. Drabkina, S.I., Zh. Eksp. Teor. Fiz., 21, No. 4 (1953).

2. Mel'nikov, M.A. and Nikitin, V.V., "Determination of the Kinetic Parameters of RDX Initiated by an Electric Spark," Fizika Goreniya i Vzryva, Vol 8, No. 4, pp. 591-593, Oct.-Dec. (1972).

CONDUCTION IN AN ALUMINIZED EXPLOSIVE DURING ESD

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JAGADISH SHARMA

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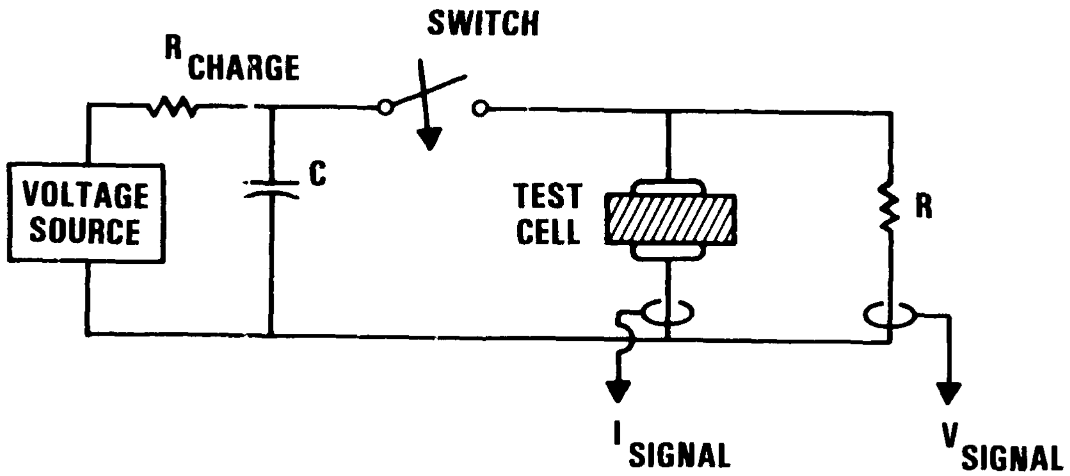
SUPPORTED BY THE OFFICE OF NAVAL TECHNOLOGY AS PART OF THE NSWC
EXPLOSIVES AND UNDERSEA WARHEADS BLOCK PROGRAM

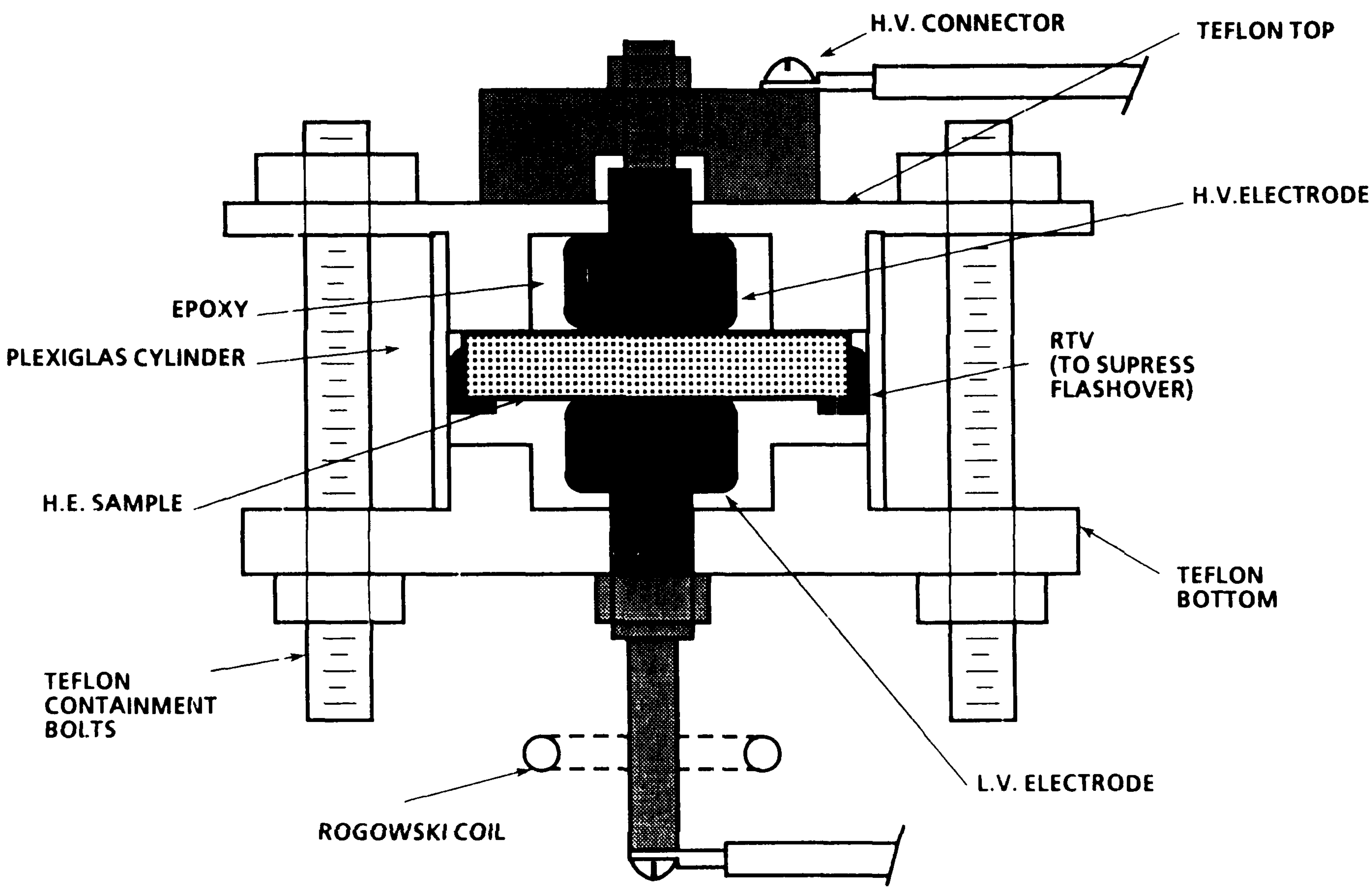
DIAGNOSTICS FOR ESD TEST



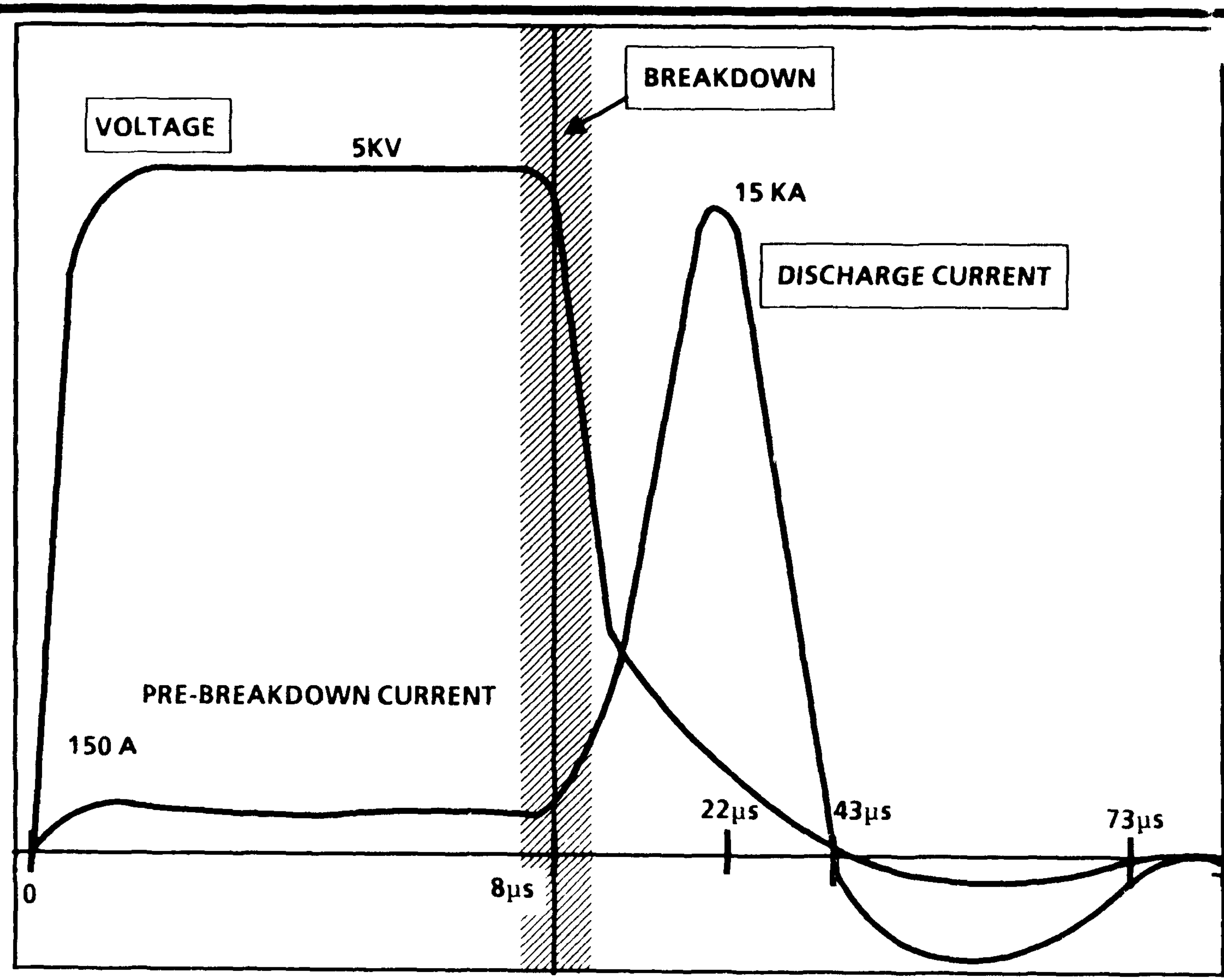
$$\text{POWER, } P(t) = V(t)\, I(t)$$

$$\text{ENERGY, } E = \int_{t_1}^{t_2} P(t)\, dt$$

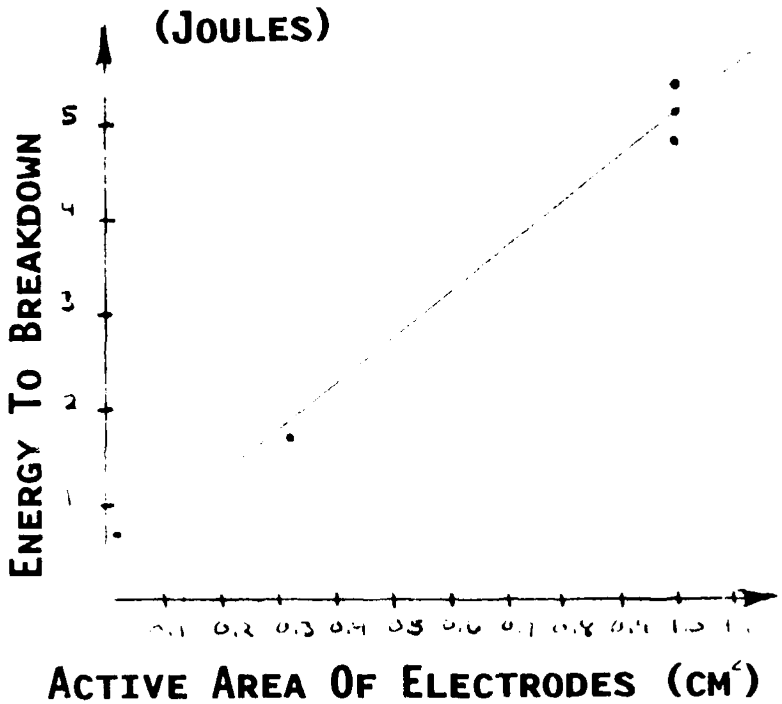
ESD TEST CELL

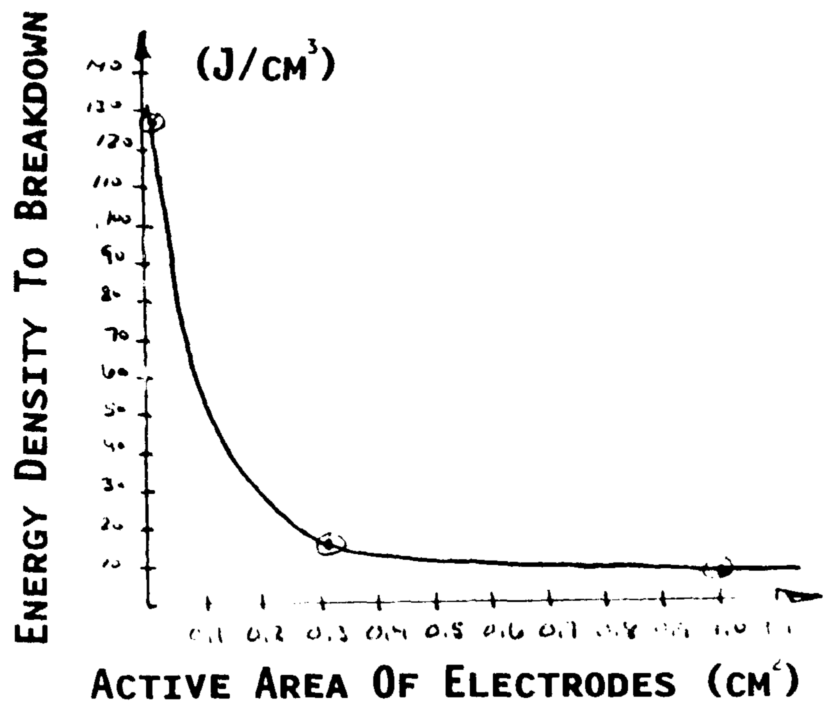


PHASES OF AN ESD EVENT



PRE-BREAKDOWN CONDUCTION





* Pre-breakdown conduction not localized.
* Energy/vol to breakdown a constant?
* Thermal breakdown mechanism.

XPS RESULTS OF DISCHARGE THROUGH PBXW-115

* NO REACTION PRIOR TO BREAKDOWN
* OBSERVED REACTION HIGHLY LOCALIZED (DIAMETER 0.5 - 1 MM).
* IGNITION ENERGY DEPOSITED IN ARC DISCHARGE.
* REACTION PATH SHOWS NEAR COMPLETE REMOVAL OF AP -> TRACES OF ClO_4^- AND Cl^-.
* RDX REMAINS IN THE DISCHARGE PATH, PARTIAL DECOMPOSITION HAS OCCURRED.

ARC DISCHARGE PHASE

* BEFORE BREAKDOWN - CONDUCTION AREA 100 MM^2.
* AFTER BREAKDOWN - DISCHARGE AREA 10^{-3} MM^2.
* DISCHARGE ARC AREA GROWS WITH INCREASING ENERGY DEPOSITION 1 MM^2.

SHOCK PHYSICS

DETONATION

* ENERGY FLUENCE, E_{det}

  $P^2 . T/RHO_{0.} U_s = 700\ J/CM^2$

* PULSE WIDTH, $T = DIA./U_s$

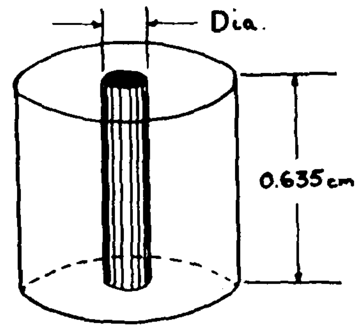
* REQUIRED DIAM. = 5 MM.

BURNING, DDT

* ENERGY FLUENCE, $E_{b,}$ 150 J/CM^2

* REQUIRED DIAM. = 1.3 MM

ESD



* LARGE ENERGY REQUIRED TO PRODUCE 5 MM DIAMETER ARC CHANNEL.

* 1 MM DIAMETER ARC CHANNELS WERE PRODUCED WITH 150 JOULES.

* DDT ENERGY FLUENCE PREDICTS ESD IGNITION SENSITIVITY.

MEL'NIKOV AND NIKITIN

$$2 \ln [g(T) / T_I] = \ln (A) - (E / R.T_I)$$

HEAT FLUX DENSITY, $g(T) = P(T) / 2(\pi)RL$

T_I - IGNITION TEMPERATURE

R(T) - ARC RADIUS

E - ACTIVATION ENERGY

P(T) - POWER

* DEVELOP THEORETICAL ESD ANALYSIS.
* INCLUDE HEAT OF REACTION.
* PREDICT ESD SENSITIVITY OF ANY MATERIAL.

CONCLUSIONS

* PRE-BREAKDOWN CONDUCTION IS NOT LOCALIZED.
* IGNITION ENERGY HIGHLY LOCALIZED.
* DEPOSITED DURING ARC DISCHARGE.
* IGNITION REQUIRES MINIMUM VOLUME OF ARC.

FUTURE WORK

* DETERMINE RELATIONSHIP BETWEEN ARC CHANNEL VOLUME AND ENERGY DEPOSITION.
* COMPARE ESD IGNITION RESULTS WITH DDT ENERGY FLUENCE DATA.
* DEVELOP THERMAL IGNITION THEORY FOR ESD IGNITION.

MEASUREMENT OF ENERGY CONTENT OF AN ELECTRIC ARC*

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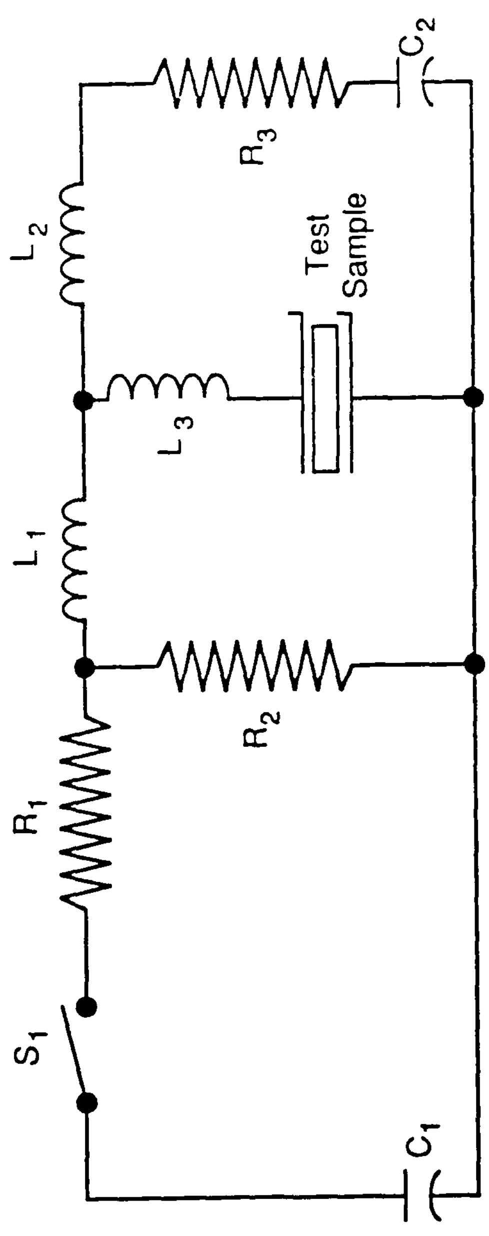
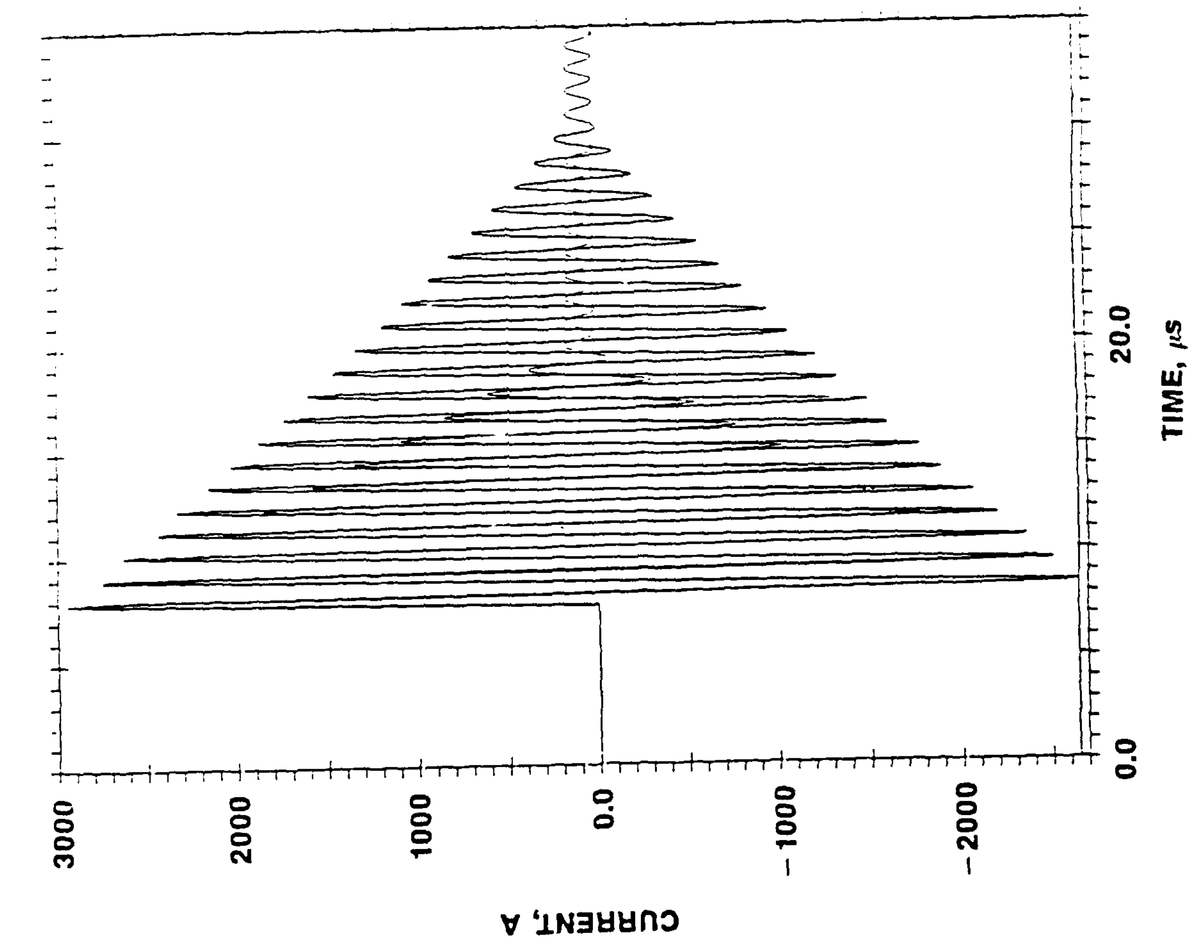
ABSTRACT

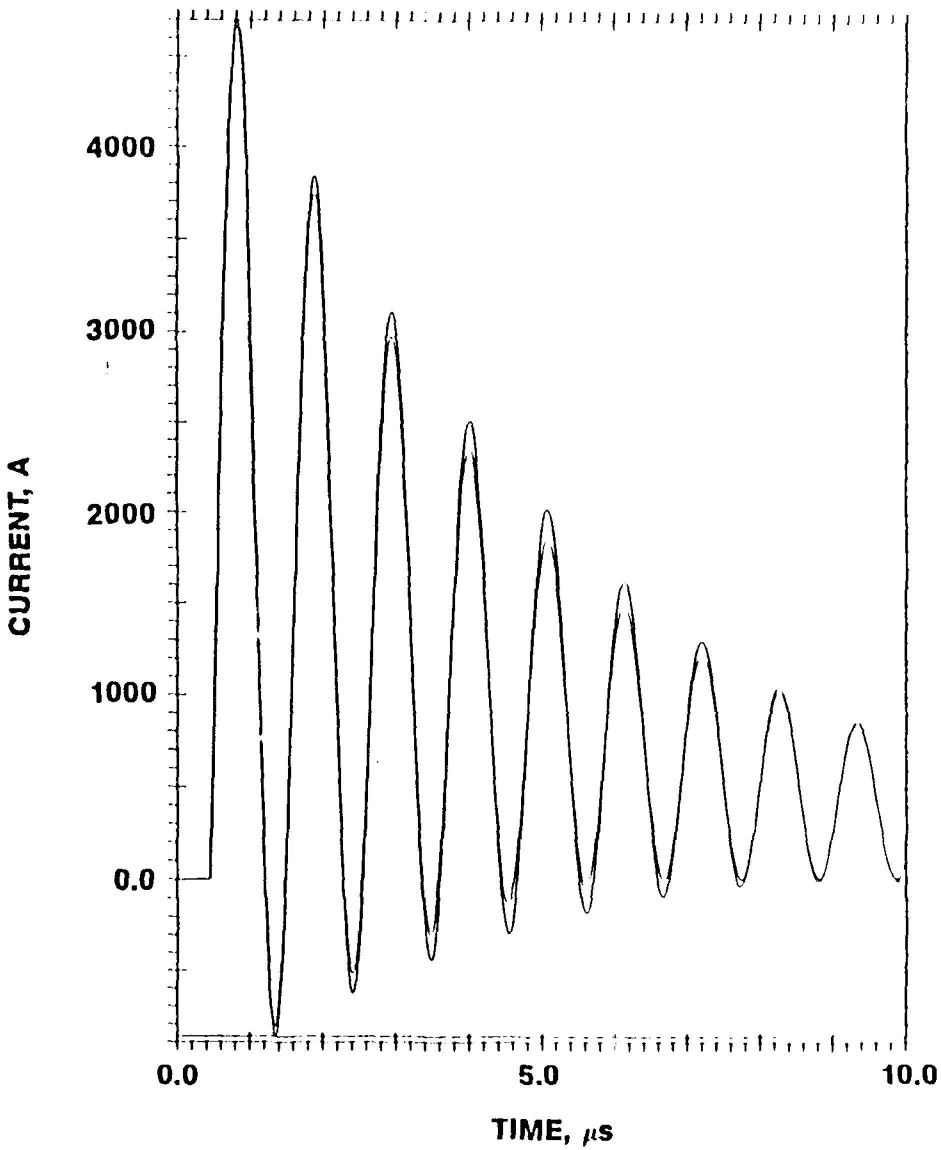
Energy density in the plasma of an electric arc is a quantity of very broad interest and has received much attention for many years. Unfortunately, a direct measurement of this energy has proved very elusive and accurate numbers are difficult if not impossible to obtain. Measurements based on the assumption that ohmic heating provides the energy are promising but making an accurate measurement of the voltage across the arc remains a particular difficulty. A methodology for inferring the voltage drop, and thus the energy deposited, is described here. This method uses circuit modeling to determine features of the easily measurable current waveform that are sensitive to the dissipative properties of the arc plasma. Comparisons of calculated waveforms to experimentally measured waveshapes are then applied to determine the energy deposited in the arc formation. A circuit was designed to provide a test bed that would allow us to optimize the sensitivity to variations in the arc behavior. Calculations of the circuit response were performed for variations in several circuit parameters and the effects monitored. Then, choosing those parameters to maximize sensitivity, a test bed was constructed to explore this concept. In this paper, we describe the methodology and show sample circuit calculations. The test bed is described and tradeoffs for study of arc characteristics are discussed. We present some measured waveforms and compare them to the calculations.



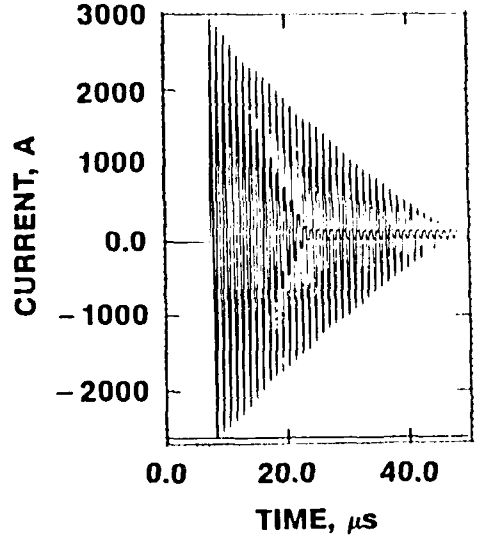
C_1
S_1
R_1
R_2
L_1
L_3
Test
Sample
L_2
R_3
C_2



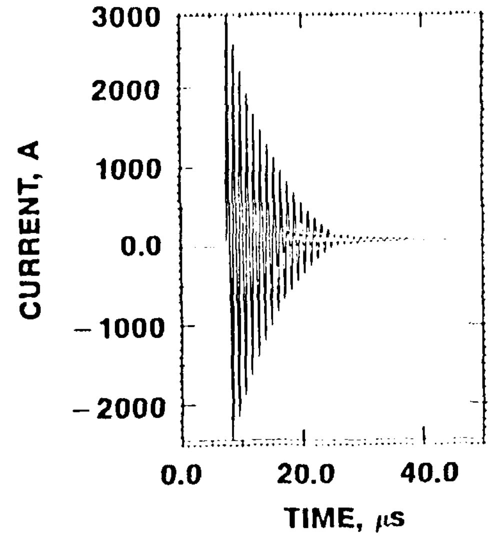
CURRENT, A
3000
2000
1000
0.0
−1000
−2000
0.0
20.0
TIME, μs


4000
3000
2000
1000
0.0
CURRENT, A
0.0
5.0
10.0
TIME, μs

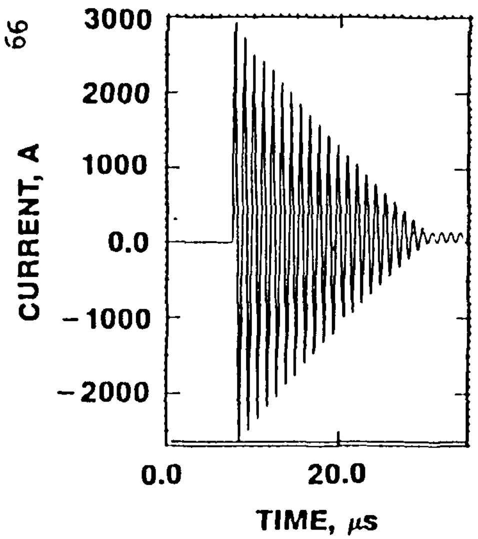
89 02 043



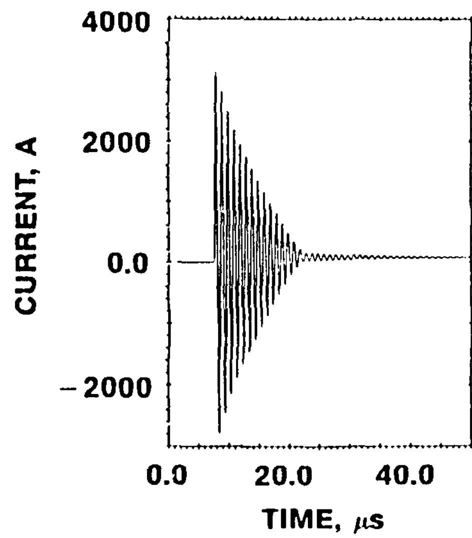
(a) $R_3 = 0$
CURVES FOR 50 AND 150 VOLTS



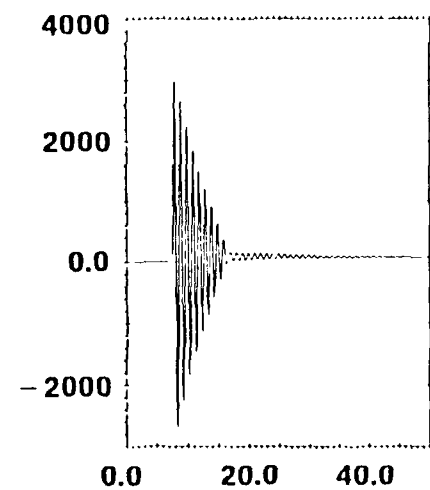
(b) $R_3 = 0.1$ ohms
CURVES FOR 50 AND 150 VOLTS



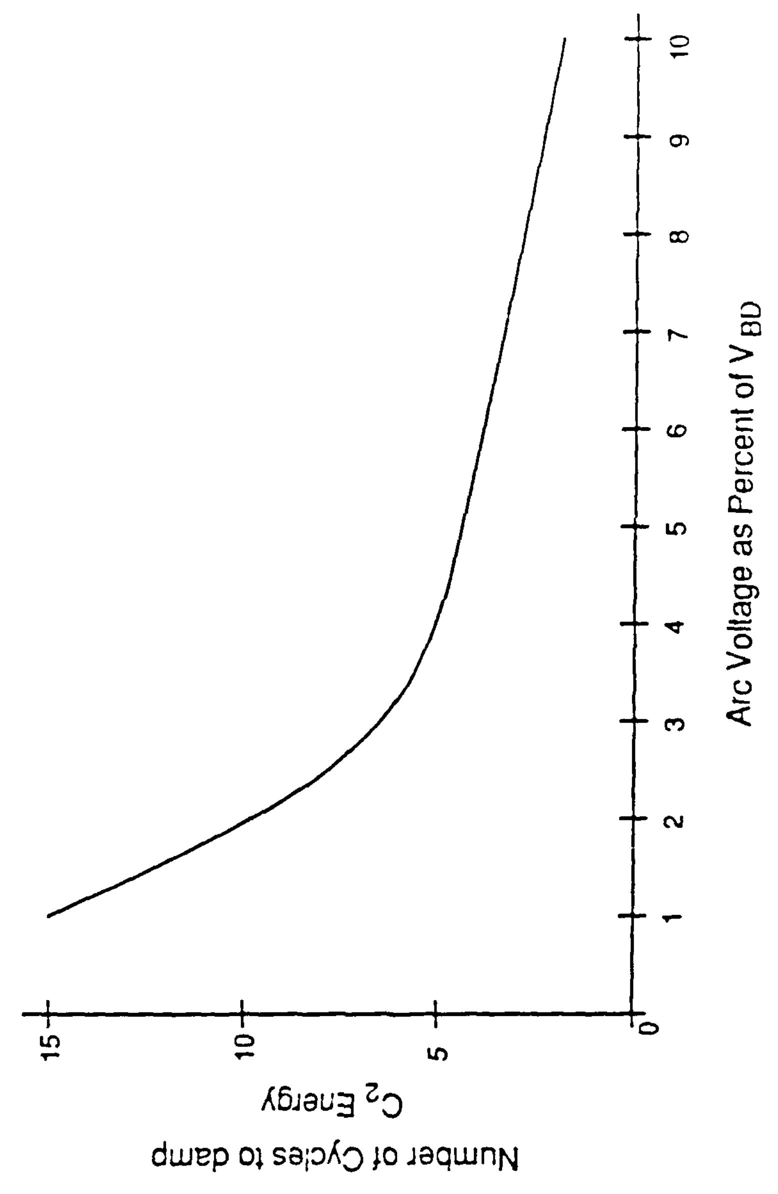
(c) $R_3 = 0$
CURVES FOR 100 AND 200 VOLTS

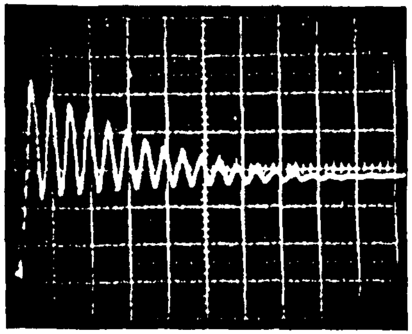


(d) $R_3 = 0.01$ OHMS
CURVE FOR 100 VOLTS

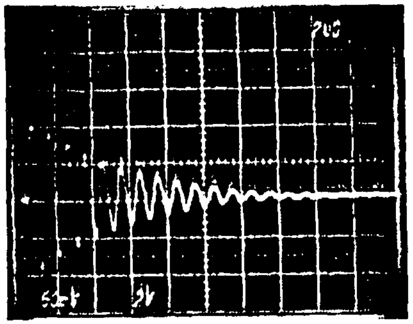


(e) $R_3 = 0.01$ OHMS
CURVE FOR 200 VOLTS

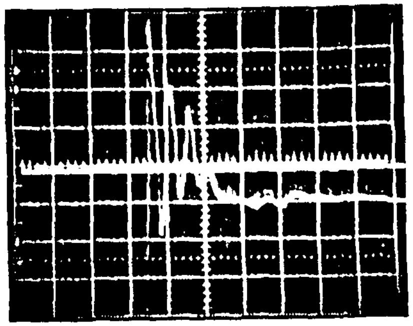

Number of Cycles to damp
C2 Energy
15
10
5
0
1
2
3
4
5
6
7
8
9
10
Arc Voltage as Percent of VBD



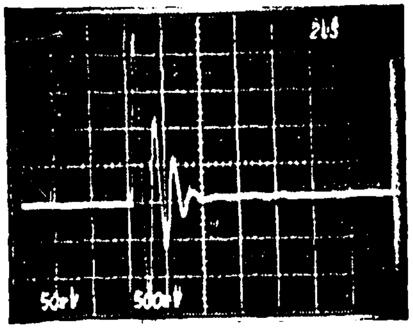
VOLTAGE
560 V/div
2 μs/div



CURRENT
3200 A/div
2 μs/div



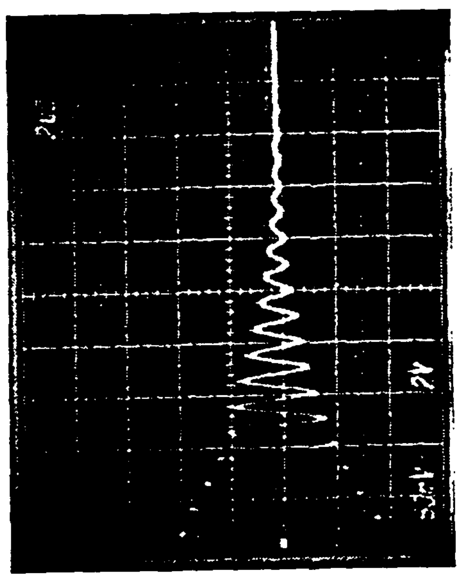
VOLTAGE
280 V/div
2 μs/div

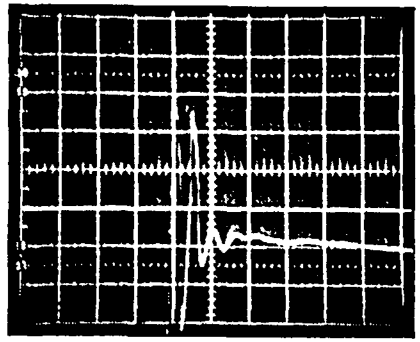


CURRENT
800 A/div
2 μs/div

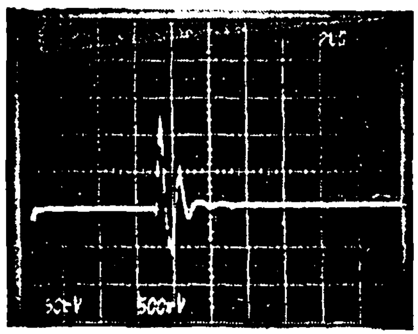
3200 A/div

2 μs/div

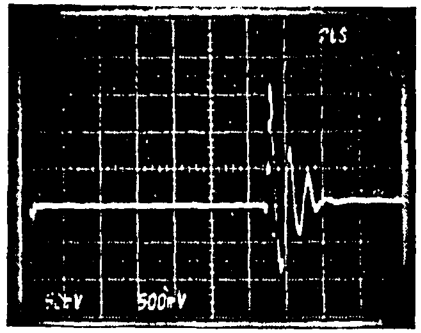




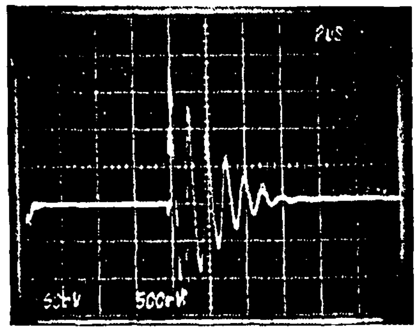
VOLTAGE
560 V/div
2 μs/div



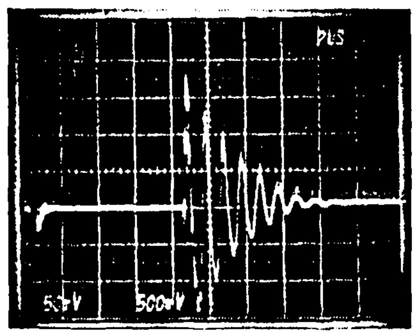
CURRENT
800 A/div
2 μs/div



FIRST DISCHARGE



SECOND DISCHARGE



FIFTH DISCHARGE

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COMBINED STIMULI SOLID PROPELLANT HAZARDS TESTING

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ABSTRACT

As a result of recent incidents involving solid composite propellant, combined stimuli hazards testing incorporating electrostatic discharge (ESD), pressure, and friction has been undertaken at Morton Thiokol, Incorporated. Such testing enables the determination of synergistic effects and accurately simulates many real world situations. Thus, greater insights can be gained into the causes of the incidents that have occurred and criteria can be established to prevent future incidents.

Testing has involved the use of an instrument capable of applying a normal load (pressure) on a propellant sample confined between two surfaces while imparting velocity/sliding friction by moving one confining surface relative to the other. Simultaneously, a known amount of electrical energy is discharged via a capacitor through the propellant sample.

The simulated ESD level necessary to cause Peacekeeper TP-H1207C propellant ignition has been quantified at specific combinations of pressure, propellant thickness, and velocity/sliding friction. The results to date indicate that the minimum ignition energy is a linear function of propellant thickness, a power function of pressure, and independent of sliding friction. Ignitions have occured under conditions as mild as 552 kPa (80 psig) pressure and 92 μJ (608 V discharged from a 500 pF capacitor) with a propellant thickness of 0.025 cm (0.010 in.). The synergistic effects of pressure and ESD result in propellant ignitions at ESD energy levels four orders of magnitude lower than at ambient pressure. These results have helped to ascertain the probable cause of the Peacekeeper PK-322 first stage motor fire.

Introduction

- The catastrophic fire of a Peacekeeper (PK) motor occurred during core extraction in December 1987

- Analysis and testing techniques developed after the Pershing II incident (West Germany) were utilized in the investigation

- Isolated stimuli such as friction or ESD failed to explain the ignition

- Hazards testing combining ESE, pressure, and friction was initiated to explore synergistic effects

- Testing simulated a worst case scenario within a PK motor

Objectives

- Determine the sensitivity of TP–H1207C propellant to combined friction, pressure, and ESE

- Establish minimum propellant ignition ESE/voltage levels as functions of:
  - Pressure
  - Propellant thickness
  - Friction
  - Surface materials

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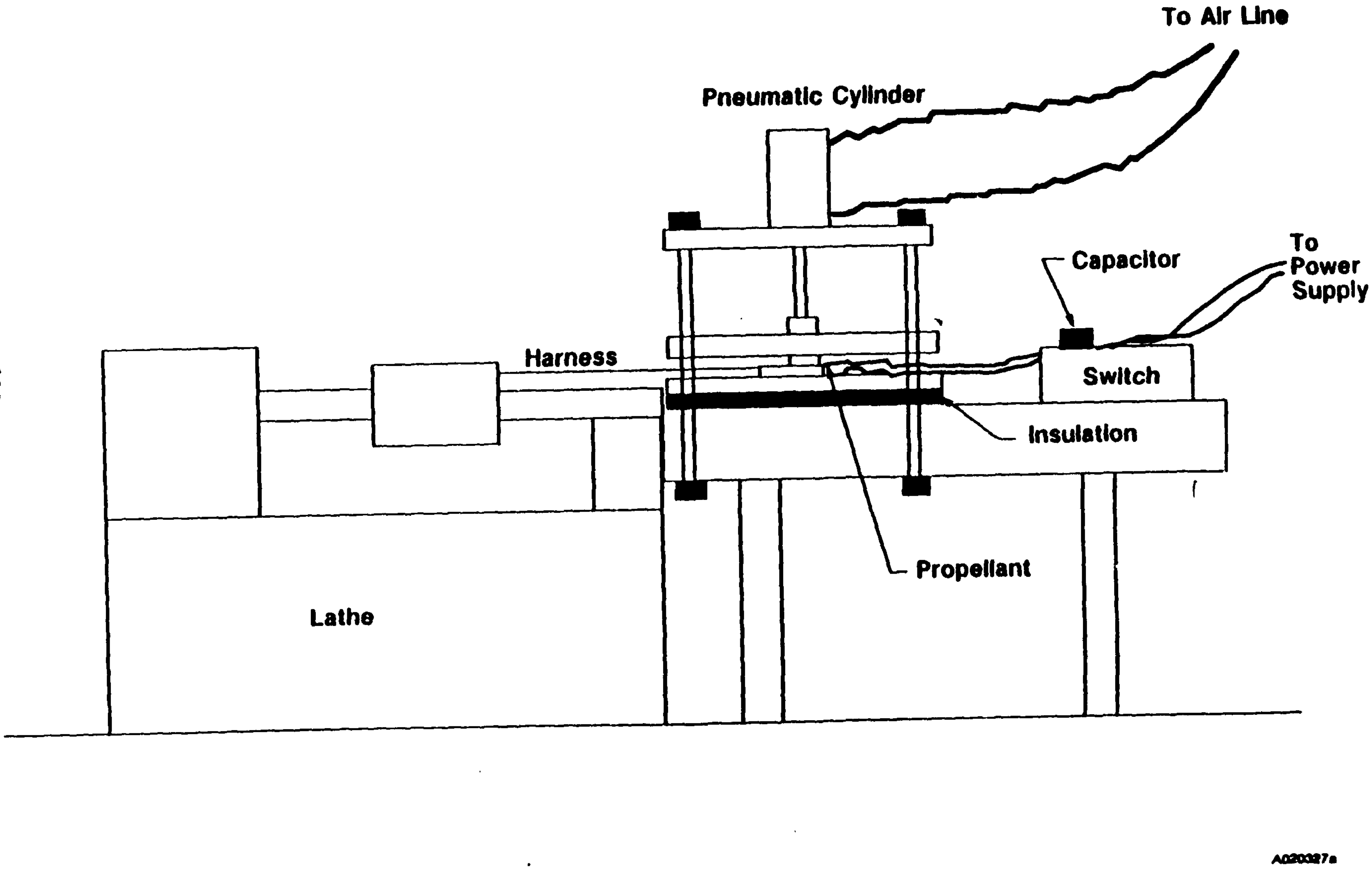
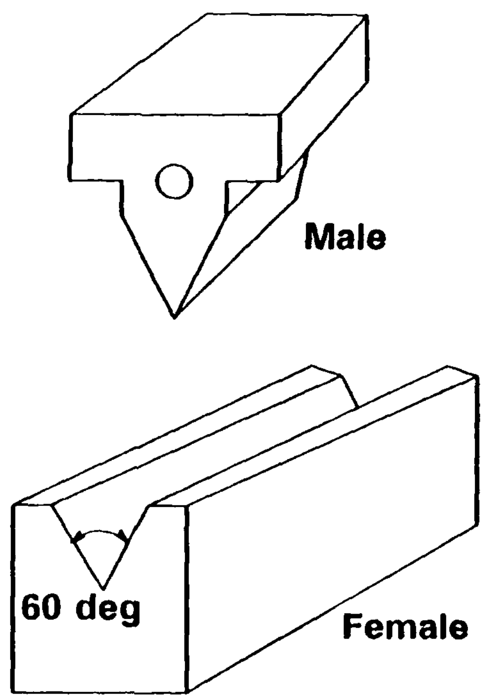
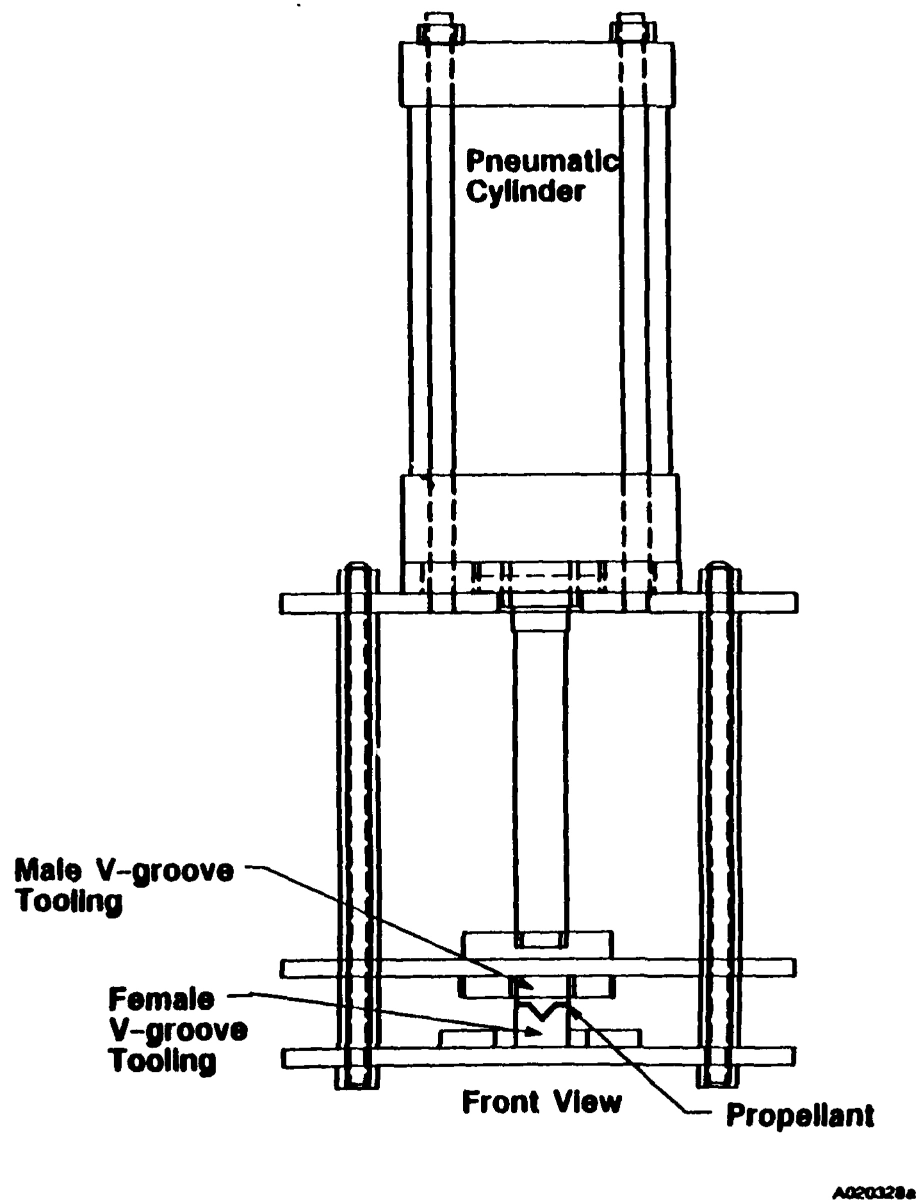
Low Load Combined Friction/Pressure/ESE Testing Apparatus



Low Load Combined Friction/Pressure/ ESE Testing Apparatus

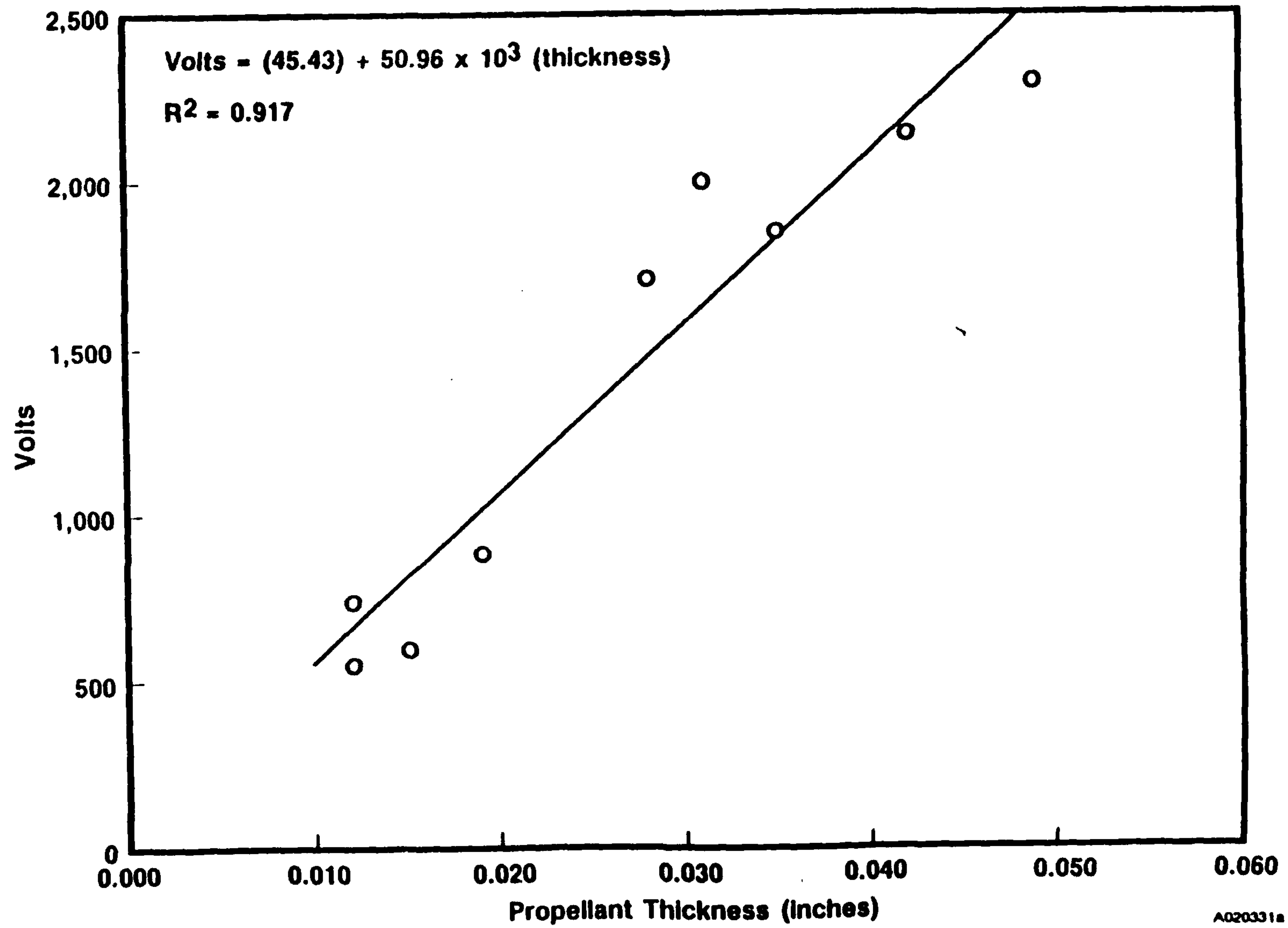




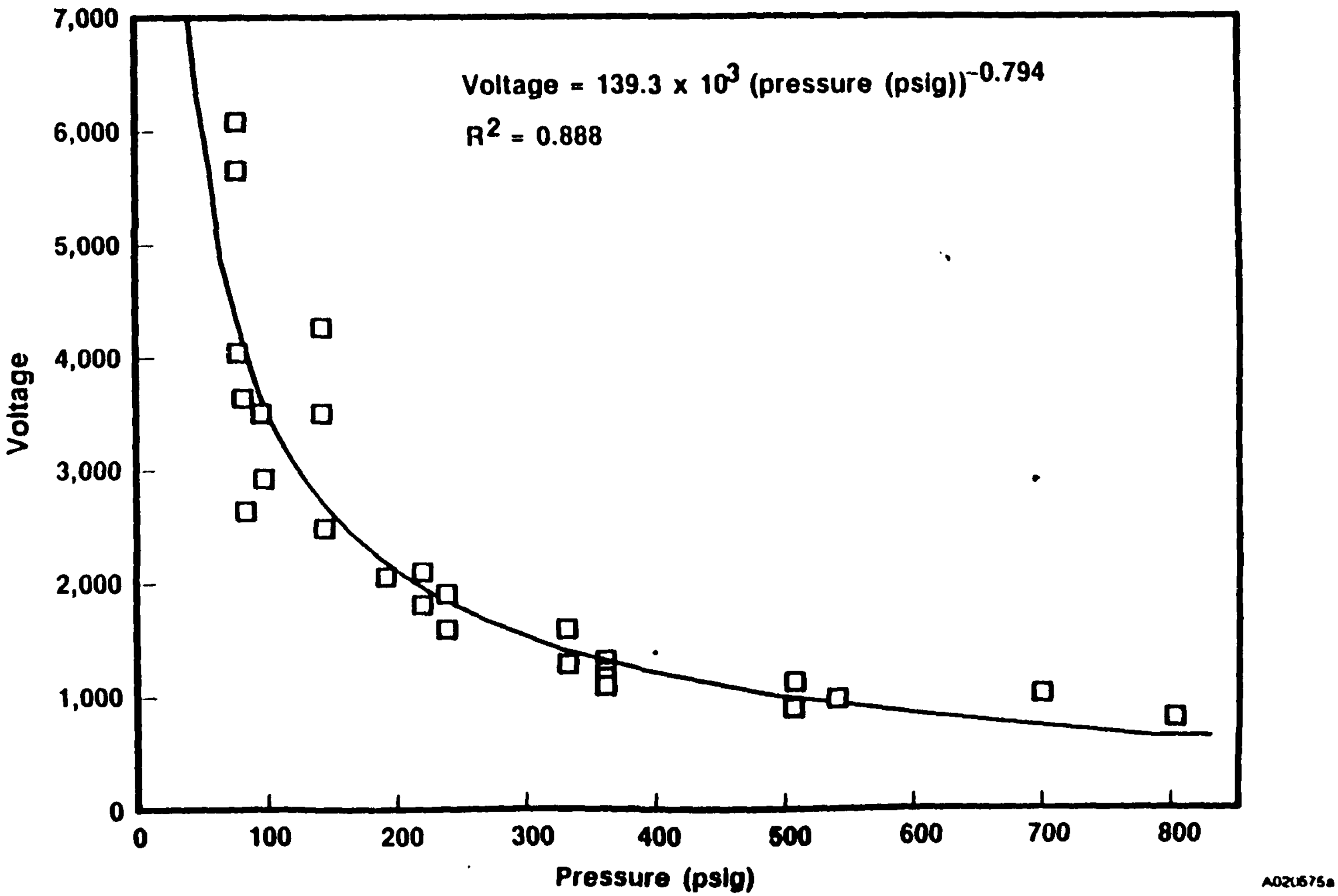
Method

- Select test parameters:
  - Pressure
  - Propellant thickness
  - Velocity
  - Tooling material
- Increase the energy of the electrical discharge in increments until ignition occurs
- Ignition = audible report

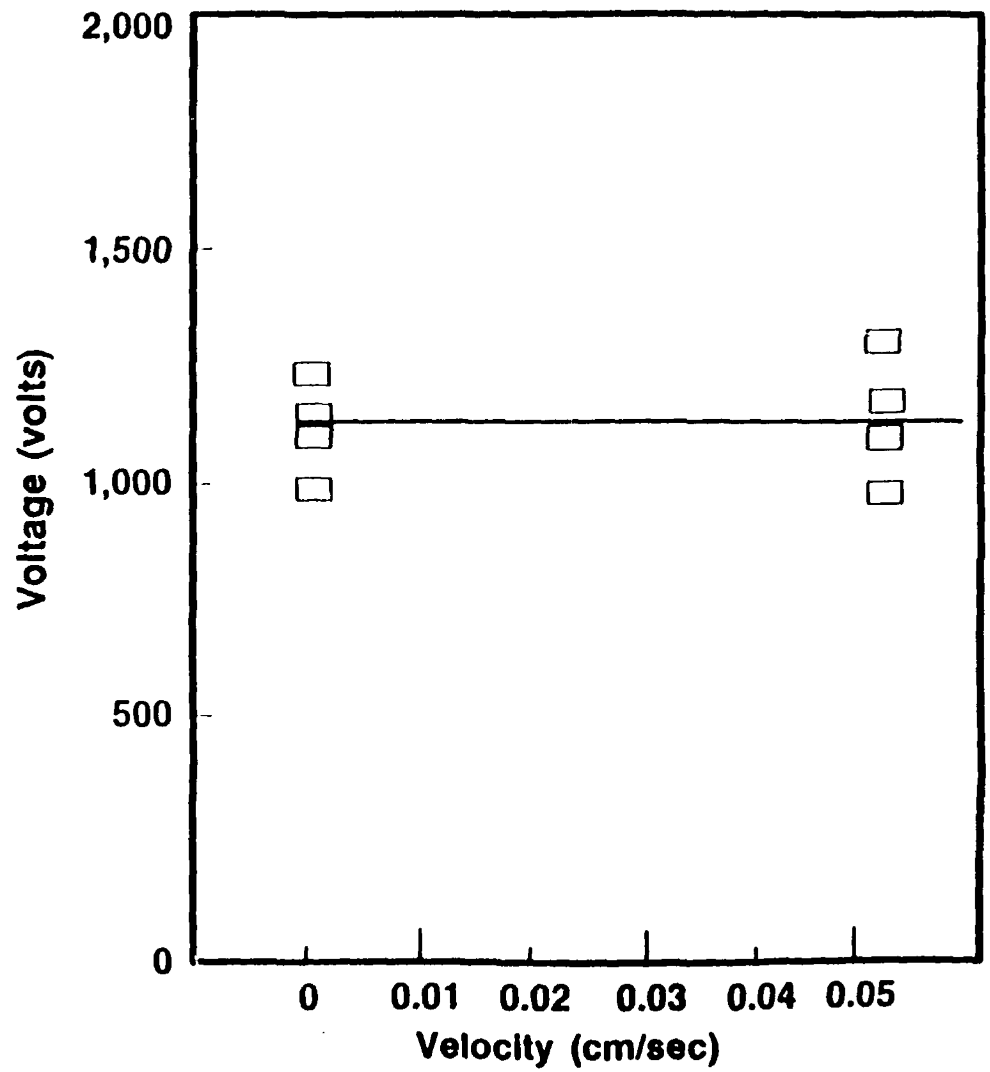
Combined Stimuli Hazards Testing Results
Propellant Thickness Versus Minimum Ignition Voltage Level
230 psig, Steel Tooling, No Velocity



TP–H1207C Combined Stimuli Hazards Tests Minimum Ignition Voltage Versus Pressure Steel Tooling, Propellant Thickness = 0.027 inch No Velocity



TP–H1207C Combined Stimuli Hazards Tests Minimum Ignition Voltage Versus Velocity 380 psig, Propellant Thickness = 0.027 inch



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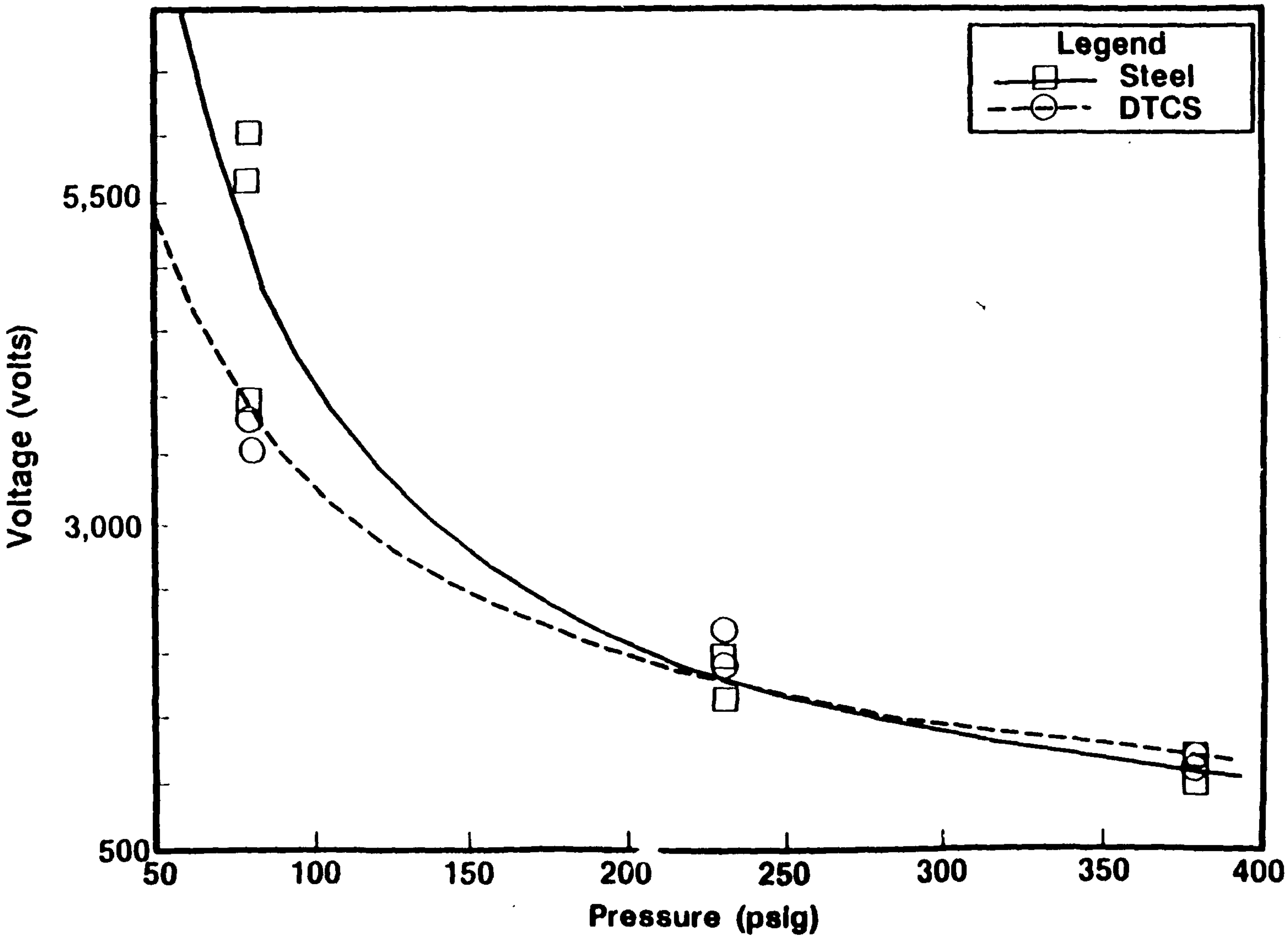
TP-H1207C Combined Stimuli Hazards Tests
Minimum Ignition Voltage Versus Pressure
Propellant Thickness = 0.027 inch



Summary of Results

- A linear correlation exists between minimum ignition energy and PK propellant thickness
- The minimum ignition energy level of PK propellant decreases as pressure increases (appears to be a power function)
- There is no significant difference between damaged Teflon coated steel and plain steel on PK propellant minimum ignition energy levels
- PK propellant minimum ignition energy level is not a function or is a weak function of friction
- Ignitions have occurred at 80 psig, no velocity, and 92 μJ/608 V

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Electrostatic Discharge (ESD) Sensitivity as Related to Combustion Characteristics

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In the last few years, Electrostatic Discharge phenomena have caused more accidents within the propulsion community than any other hazard. Despite much research on ESD, little is known about the *severity of a reaction* that is triggered by an ESD event. In this work we have investigated the ESD sensitivity as it relates to the ignition characteristics of a váriety of propellants.

An attempt was made to understand how the propellants respond to an ESD stimulus. From this work we showed that the electrical properties alone are not sufficient when looking at a solid rocket propellant's ESD hazard. In other words, the relative propellant's reactivity must also be included when studying the ESD hazard. The propellant's response to the ESD stimulus must be understood. To understand such a response, we developed the spark ignition experiment. Preliminary data from this experiment can be directly correlated to both burn rate data and CO2 laser ignition data. Electrical properties (such as volume resistivity, dielectric constant and dielectric breakdown field strength) data alone do not accurately indicate the propellants response to an ESD event. Such data are only obtainable from spark ignition experiments and from comparison with measured combustion properties. Additional research is required in the area of spark initiation experiments of solid rocket propellants.

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ELECTROSTATIC DISCHARGE (ESD) SENSITIVITY AS RELATED TO COMBUSTION CHARACTERISTICS

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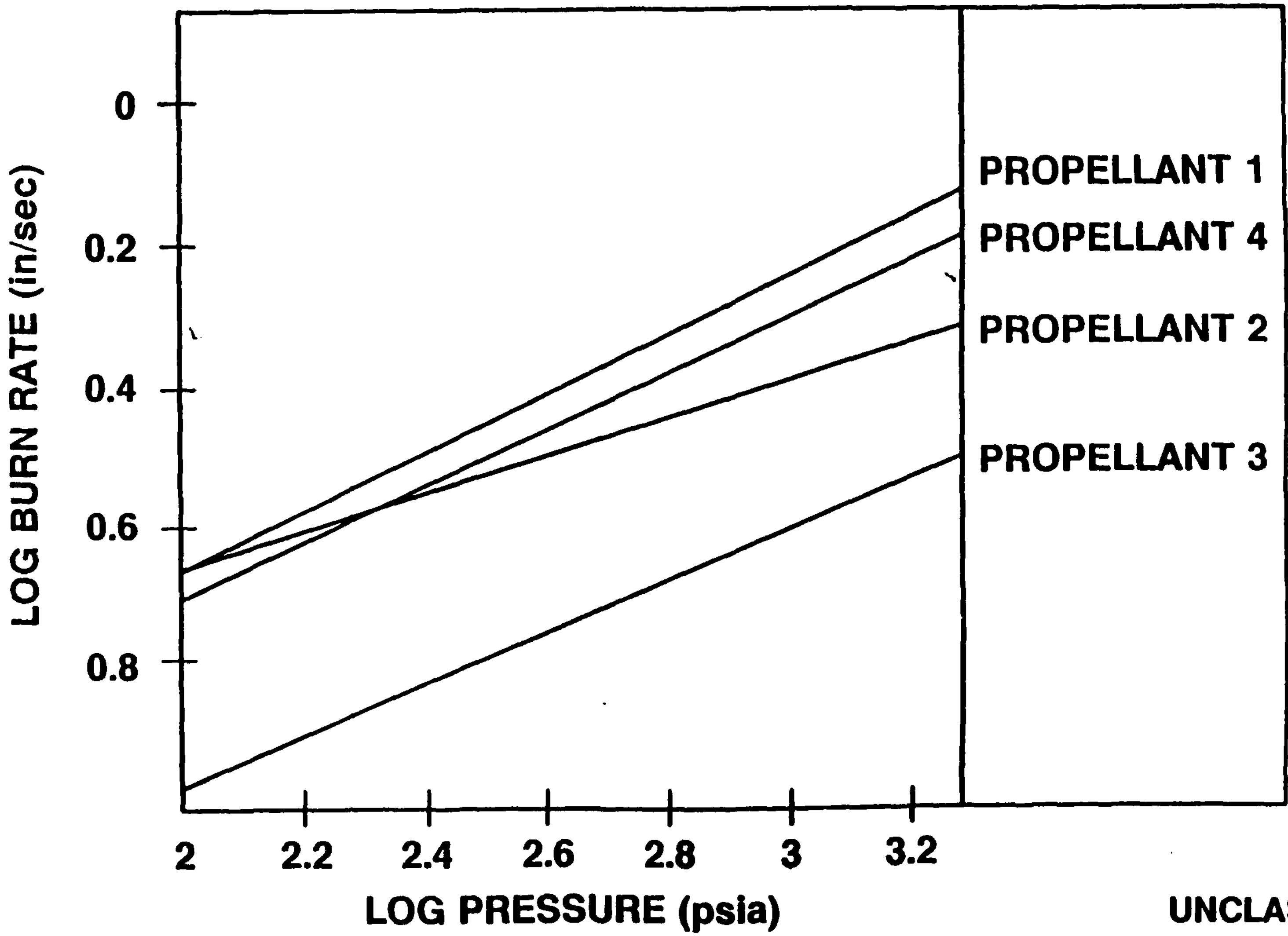
BURN RATE (IN/SEC) VERSUS PRESSURE DATA FOR THE FOUR PROPELLANT SAMPLES



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PROPELLANT FORMULATIONS

PROPELLANT NO.	AL WT% (PARTICLE SIZE)	WT% TOTAL NON-CONDUCTING SOLID	BINDER TYPE
1	20 (15 μm) + Fe_2O_3	~ 70 AP	HTPB[a]
2	22 (60 μm)	~ 70 AP, HMX	HTPB
3	19 (13 μm)	~ 70 AP	HTPB
4	16 (30 μm) + Fe_2O_3	~ 70 AP	HB[b]

[a] HTPB - HYDROXY-TERMINATED POLYBUTADIENE

[b] HB - POLYBUTADIENE ACRYLIC ACID ACRYLONITRILE

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WHAT AND WHY?

- CORRELATION BETWEEN COMBUSTION CHARACTERISTICS AND ESD SENSITIVITY
- IMPORTANT TO KNOW HOW PROPELLANTS REACT TO ESD

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OUTLINE

- BURN RATE, LASER IGNITION, AND SPARK IGNITION TESTS
- TEST RESULTS, ELECTRICAL PROPERTIES AND CHEMICAL FORMULATIONS
- NEED FOR COMBUSTION CHARACTERISTICS IN ESD HAZARD ASSESSMENTS

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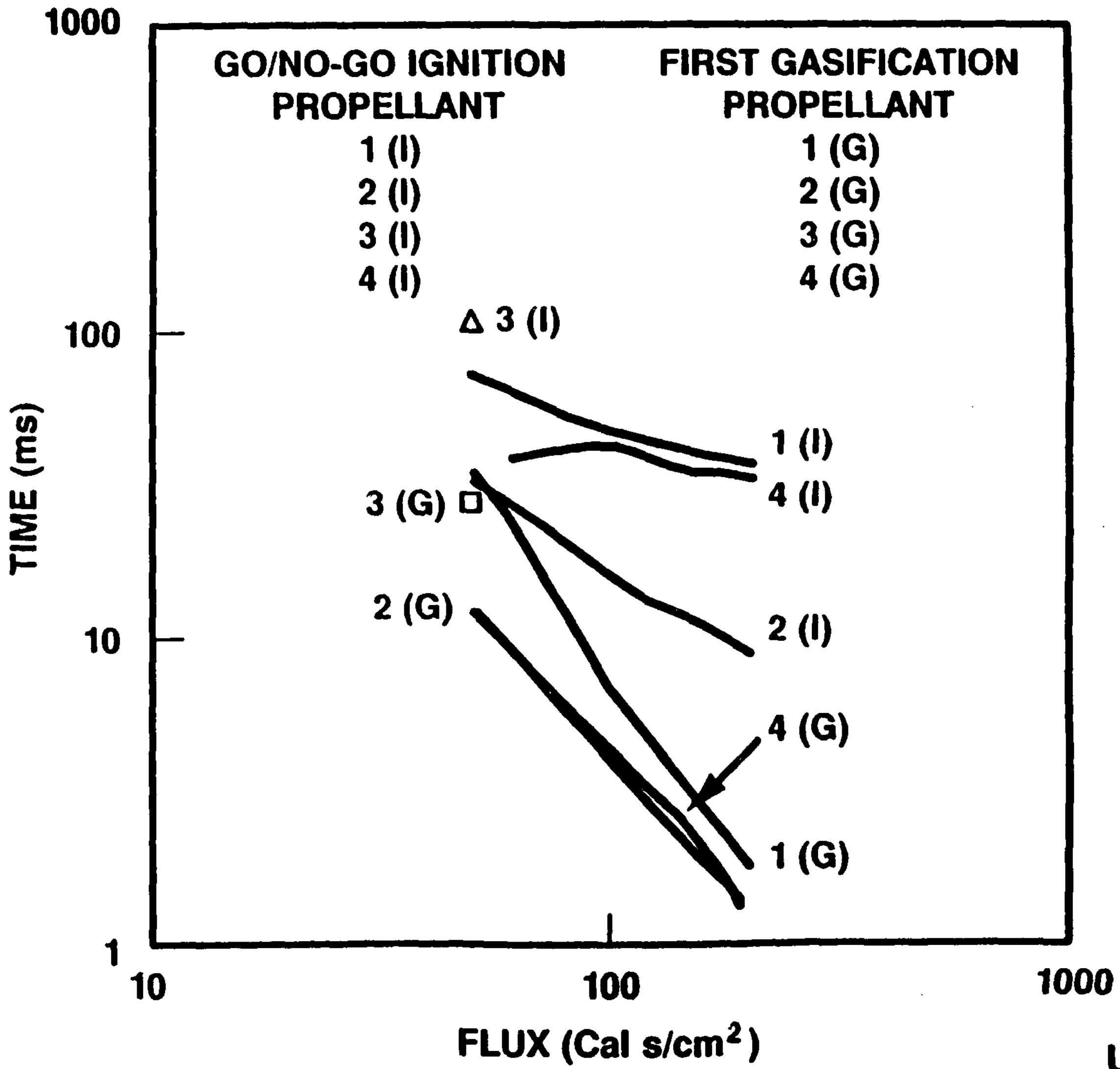
COMPOSITE GRAPH OF CO_2 LASER IGNITION DATA AT 1 Atm FOR ALL FOUR PROPELLANTS



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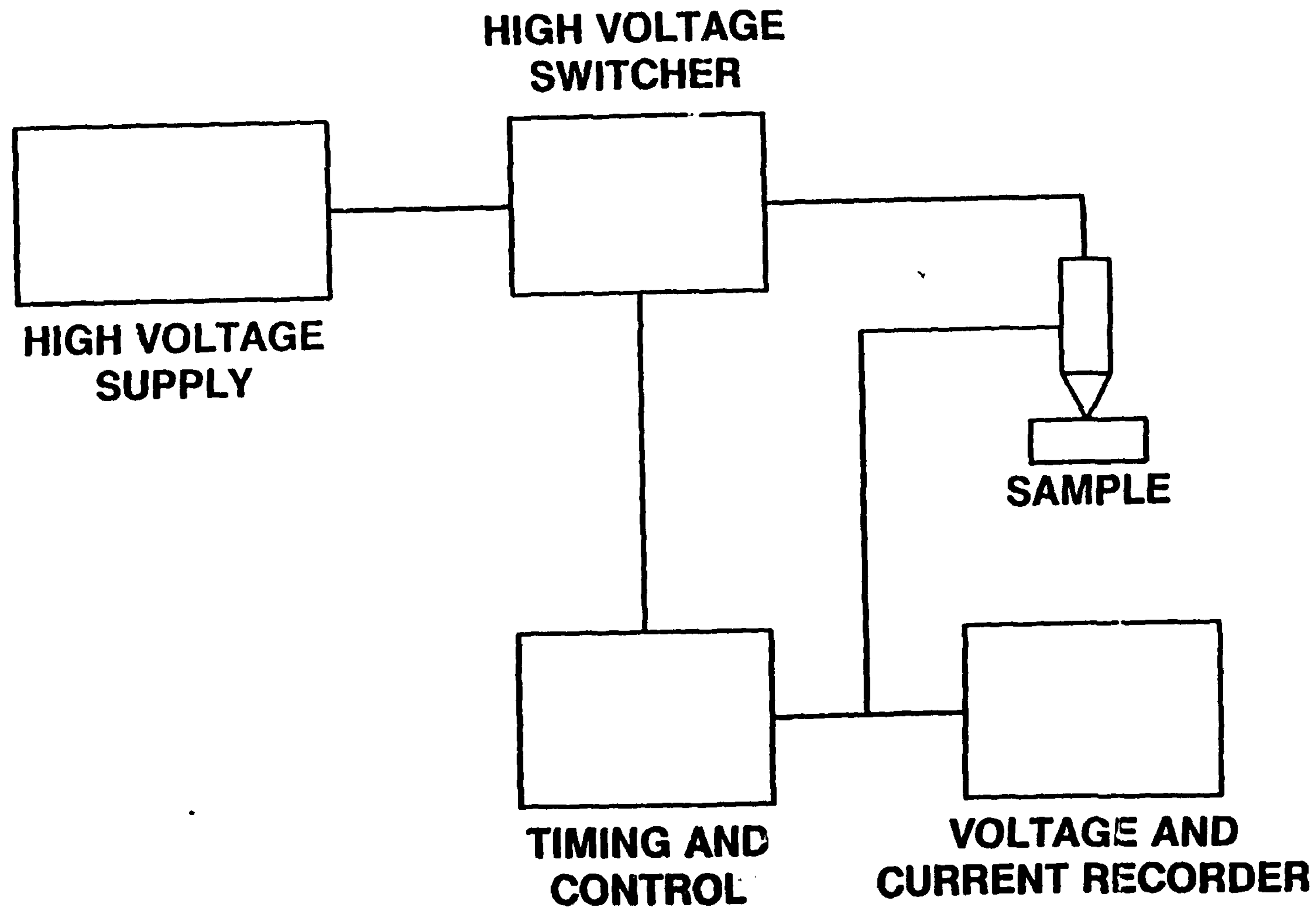
SPARK IGNITION TEST SETUP



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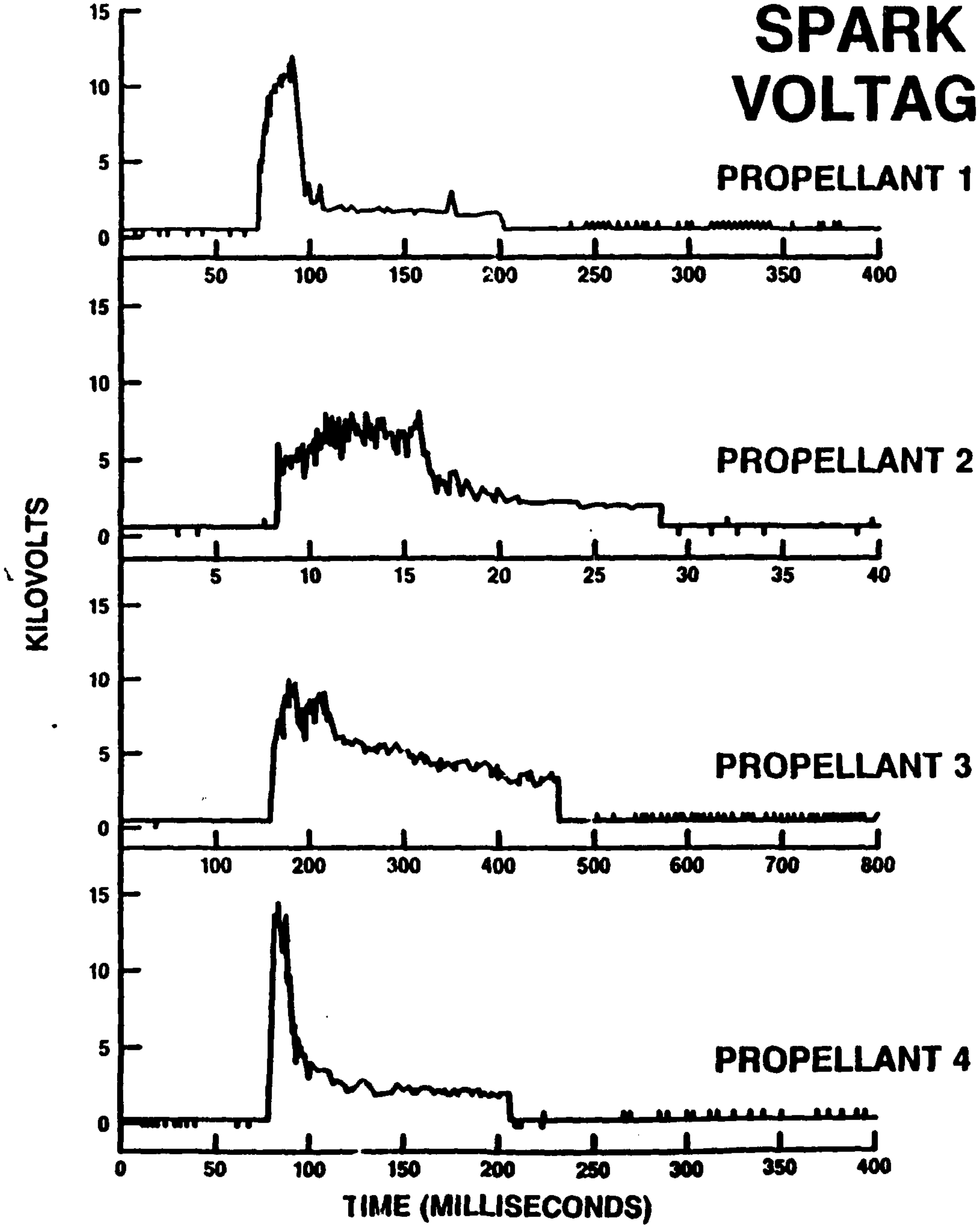
SPARK IGNITION VOLTAGE TRACES



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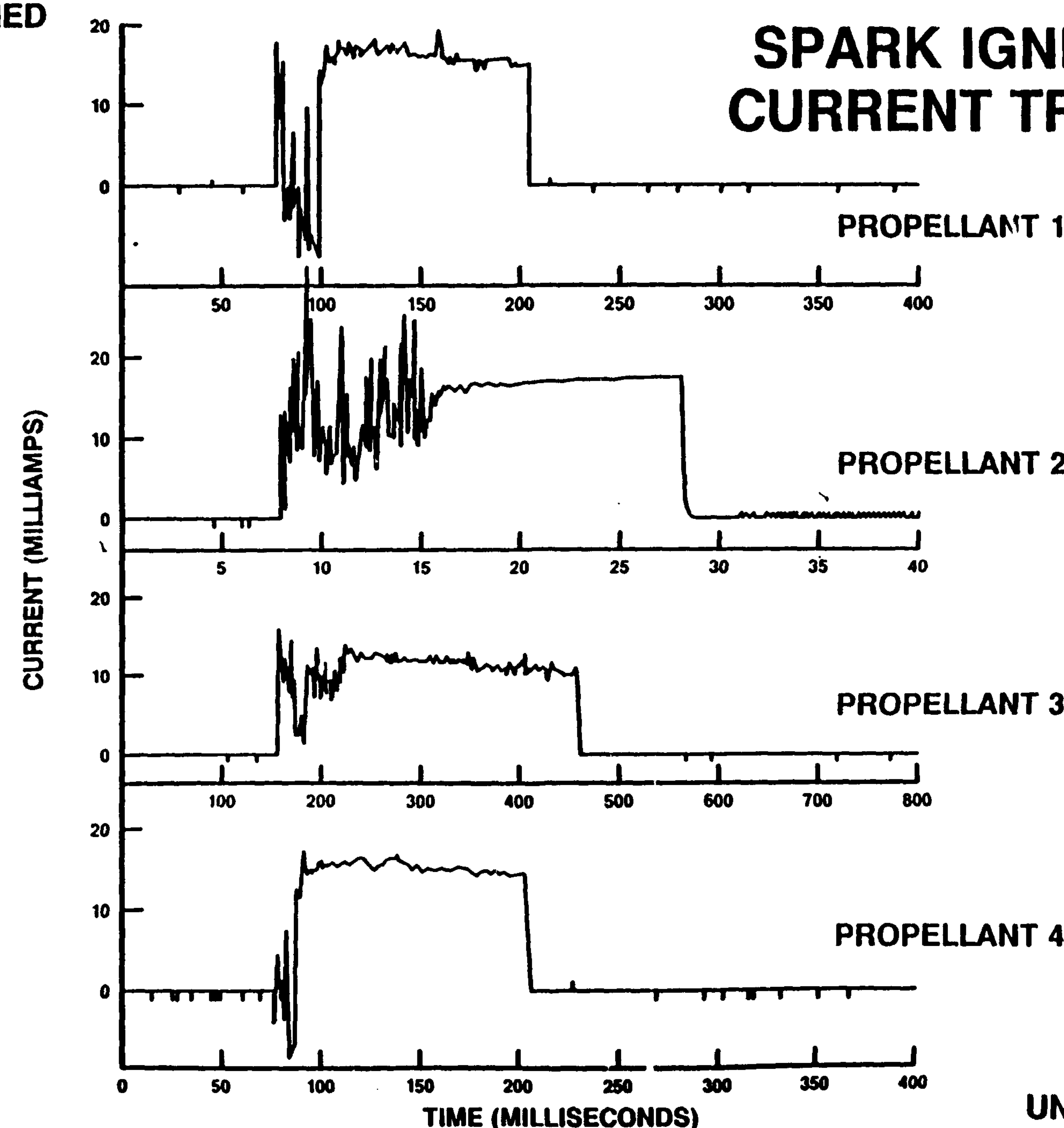
SPARK IGNITION CURRENT TRACES



ELECTRICAL DATA

PROPELLANT NO.	P_{IMP}[c] CALCULATION (Ω -m)	DIELECTRIC CONSTANT[d]	DISSIPATION FACTOR[d]	DIELECTRIC FIELD STRENGTH[e] V/m
1	$12\text{-}372 \times 10^{10}$	8.38-9.216	0.0-0.01[illegible]	$0.67\text{-}1.06 \times 10^{6}$
2	2.20×10^{7}	9.15-9.82	0.0046	$0.45\text{-}1.52 \times 10^{6}$
3	1.29×10^{10}	7.91-9.4	0.004-0.0046	$0.48\text{-}1.25 \times 10^{6}$
4	3.06×10^{10}	10.8-14.55	0.18	$0.96\text{-}1.50 \times 10^{6}$

[c] P_{IMP} - IMPROVED PERCOLATION CALCULATION

[d] DATA TAKEN AT 1 kHz, 60°F AND RH LESS THAN 30%

[e] DATA TAKEN AT 60°F, RH LESS THAN 30%

COMBUSTION DATA

PROPELLANT	BURN RATE[1] (INCHES PER SECOND)	LASER[2] IGNITION (Cal s/cm^2)	SPARK[3] IGNITION (JOULES)
1	0.22	69	4.0
2	0.22	33	0.9
3	0.11	113	6.5
4	0.20	37	1.5

NOTES
1. BURN RATE DATA AT 100 PSIA
2. LASER IGNITION DATA AT 50 PSIA
3. SPARK IGNITION DATA AT 1 ATM

CONCLUSIONS

- ELECTRICAL PROPERTIES ALONE DO NOT ADEQUATELY PREDICT HOW PROPELLANTS WILL REACT TO ESD

- COMBUSTION DATA MUST BE CONSIDERED WHEN MAKING ESD HAZARD ASSESSMENTS

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Rocket Propellant Hot Spot Ignition Simulation[1]

A.M. Mellor and D. R. Stoops[2]
Vanderbilt University, Nashville, TN

T.P. Rudy and R.W. Hermsen
United Technologies Chemical Systems
San Jose, CA

A proposed set of spark, shock (exploding wire), and thermal (hot wire) sensitivity tests for solid rocket propellants is discussed. In each, a macro–hot spot is created within a propellant sample. These tests appear unique in that they should determine minimum ignition energy requirements for individual propellant formulations and thus address equivalency of energy thresholds for each mode of energy input. A review[3] of the different electrode configurations used to measure minimum spark ignition energies in gases and fuel sprays provides a basis for experimental geometric design and parameter range selection. Specifically, ignition energy obtained as a function of energy input rate, input duration, and "gap width" should reveal those combinations which exhibit lowest threshold initiation requirements.

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[1]Prepared for presentation at Army Research Office Workshop on ESD Ignition of Composite Solid Propellants, Vanderbilt University, Nashville, TN, 18–19 April 1989. Sponsored by UT/CSD PO 276249 and NSF Grant ENG–8712997.

[2]Drexel University, Philadelphia, PA

[3]Mellor, A.M., Stoops, D.R., Rudy, T.P. and Hermsen, R.W., "Optimization of Spark and ESD Propellant Sensitivity Tests: A Review," pp. 213–221, JANNAF PSHS Mtg. Proc., CPIA Publ. 477, Vol. I (1988); Propellants, Explosives, and Pyrotechnics, to appear (1989).

CONCEPT OF HOT SPOT HAZARD TEST

- Kent and Rat (1982) on ESD
  - At sufficient applied potential, internal mini–arcs initiate ($A\ell_2O_3$ breakdown) and precede macroscopic cracking of propellant; ρ_V drops significantly
  - If sufficient energy enters sample, ignition will occur

- Need test to characterize E_{min}, the sufficient energy, for risk analysis
  - Based on similar work for premixed gases and fuel sprays
  - Optimization of experimental variables required; measure energy to propellant prior to ignition; E_{min} is property of energetic material, not of test method

- Design for non–ESD inputs as well: thermal, exploding wire
  - Single, similar geometry for direct comparisons of data and ease of analysis
  - Compare E_{min}'s from each to see if ESD is thermal; effects other than raising E due to blast wave in ESD and exploding wire (ultra–short durations as in laser sparks of Syage et al., 1987 JANNAF Comb): damage?

MINIMUM SPARK IGNITION ENERGY BACKGROUND

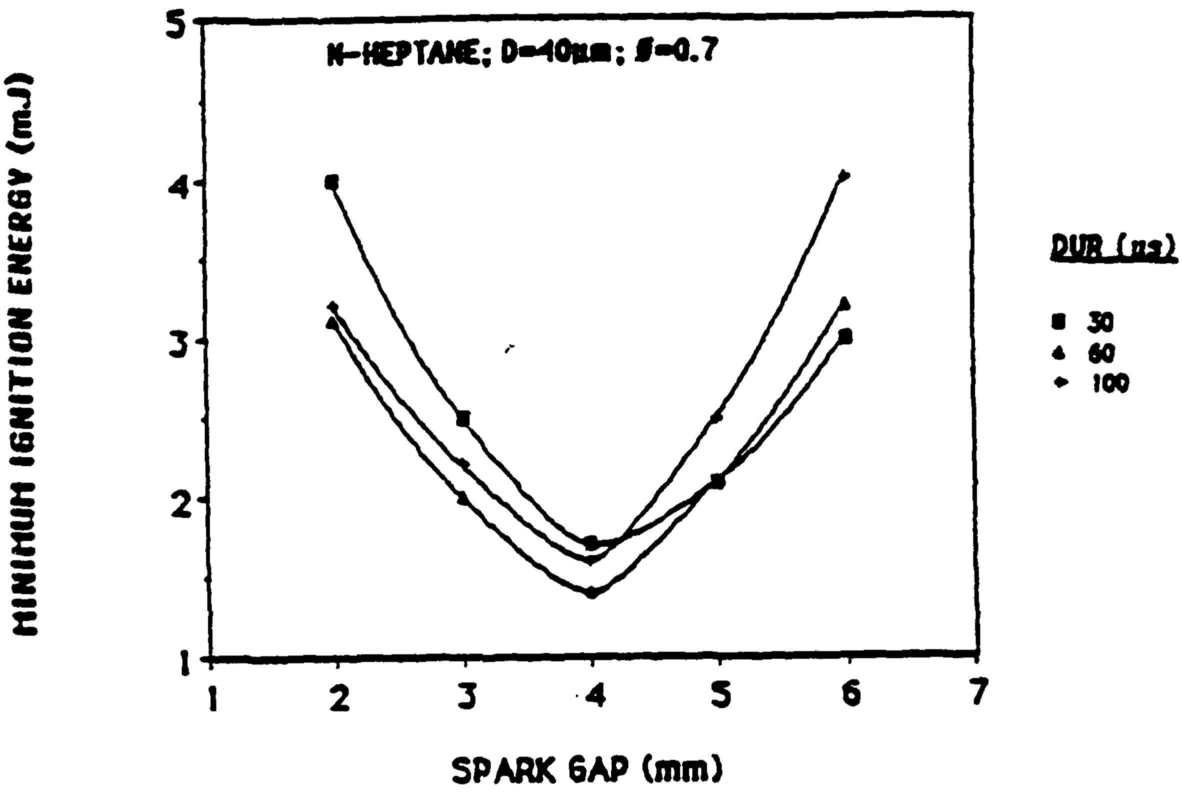
(Mellor et al., 1988 PSHS; Williams, 1989 PSHS)

Findings with premixed gases and fuel sprays, where electrodes inserted into confined medium to be ignited:

- Optimum spark gap width minimizes E
  - Too large, excessive material ignited
  - Too small, excessive heat loss to electrodes
- Optimum spark duration minimizes E
  - Too long, energy added after ignition
  - Too short, blast/shock wave distributes energy over excessive material
- Optimum electrode size and shape minimizes E
  - Heat loss vs durability (plate electrodes)
  - Field strength concentrations (needle electrodes)
- Optimum electrode material minimizes E
  - $E \propto T_{BP}^{0.25}$ (Ballal and Lefebvre, Combust. Flame 1975)
  - For confined explosives, Larson et al. (1986 PSHS) report $\frac{1}{2}CV_0^2$ - sample mass and free volume - brass vs SS dependence

E vs GAP WIDTH AND DURATION (DANIS, 1987)

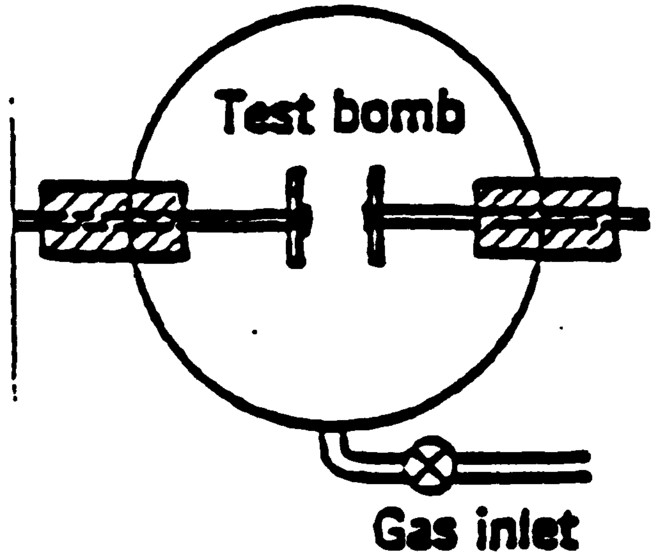
Ground side flat ended, high voltage side pointed 1 mm diameter 316 SS electrodes



TYPICAL EXPERIMENTAL CONFIGURATIONS AND SPARK VARIATIONS

Premixed Gases (Stagnant)

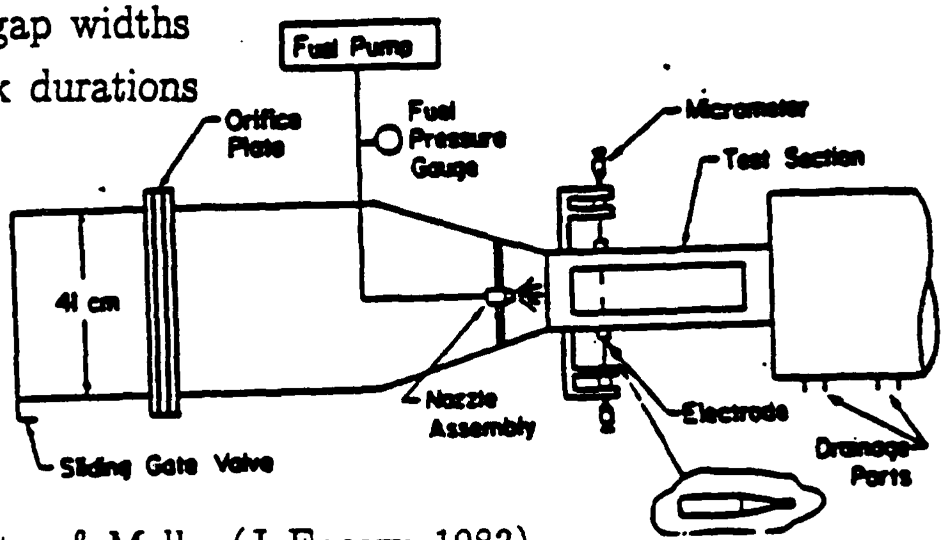
2 – 9 mm spark gap widths
30 – 100 μs spark durations



Blanc et al. (3rd Comb. Symp., 1949)

Fuel Sprays (Flowing past Electrodes)

2 – 9 mm spark gap widths
60 – 100 μs spark durations

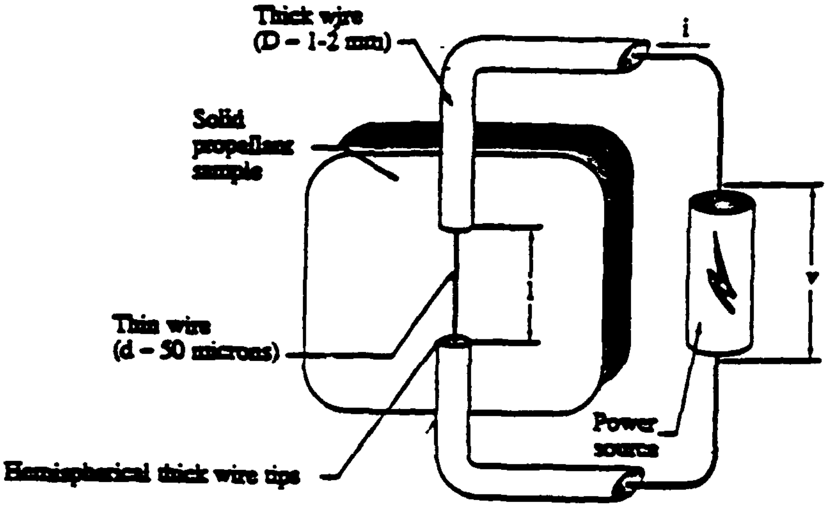


Peters & Mellor (J. Energy, 1983)

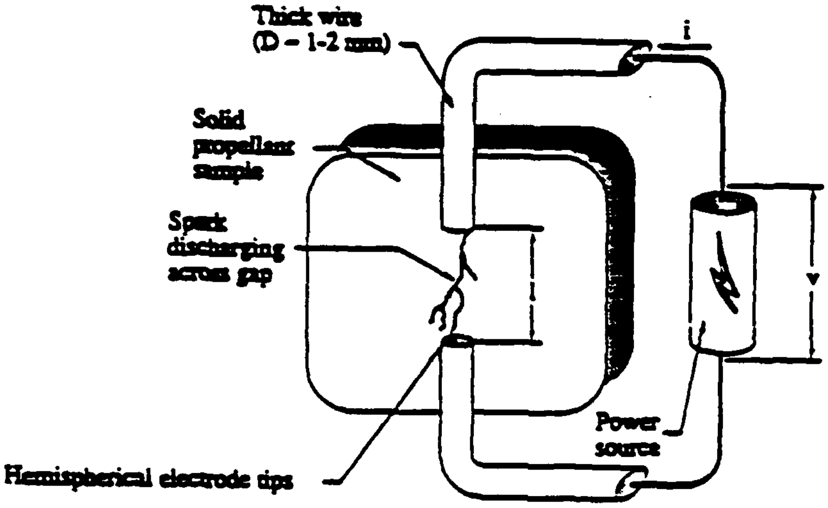
Note all optimal durations are in arc discharge régime and electrodes are immersed in medium to be ignited

HOT SPOT HAZARD TEST CONFIGURATIONS

- Thermal/Exploding Wire



- Spark



- Wires cast in solid propellant cubes
- Thin wire or electrode gap creates (macro–)hot spot

MEASUREMENT OF E TO SAMPLE BEFORE IGNITION

$$E = \int_0^{t_{ign}} V(t)I(t)dt$$

- t_{ign} = time to ignition from start of energy input
- $V(t)$ = time–varying voltage across sample
- $I(t)$ = time–varying current through shunt resistor in series with gap. Larson et al. (1986 PSHS) report value of shunt resistor affects $\frac{1}{2}CV_0^2$ for igniton. It should not affect E.
- Calibrate with phase–change material
- See also Schneider et al. (1989 PSHS): square wave V(t)'s applied can fluctuate during mini–arcs

Ignition requires self–sustaining reaction and thus essentially complete consumption of sample. t_{ign} can be determined by

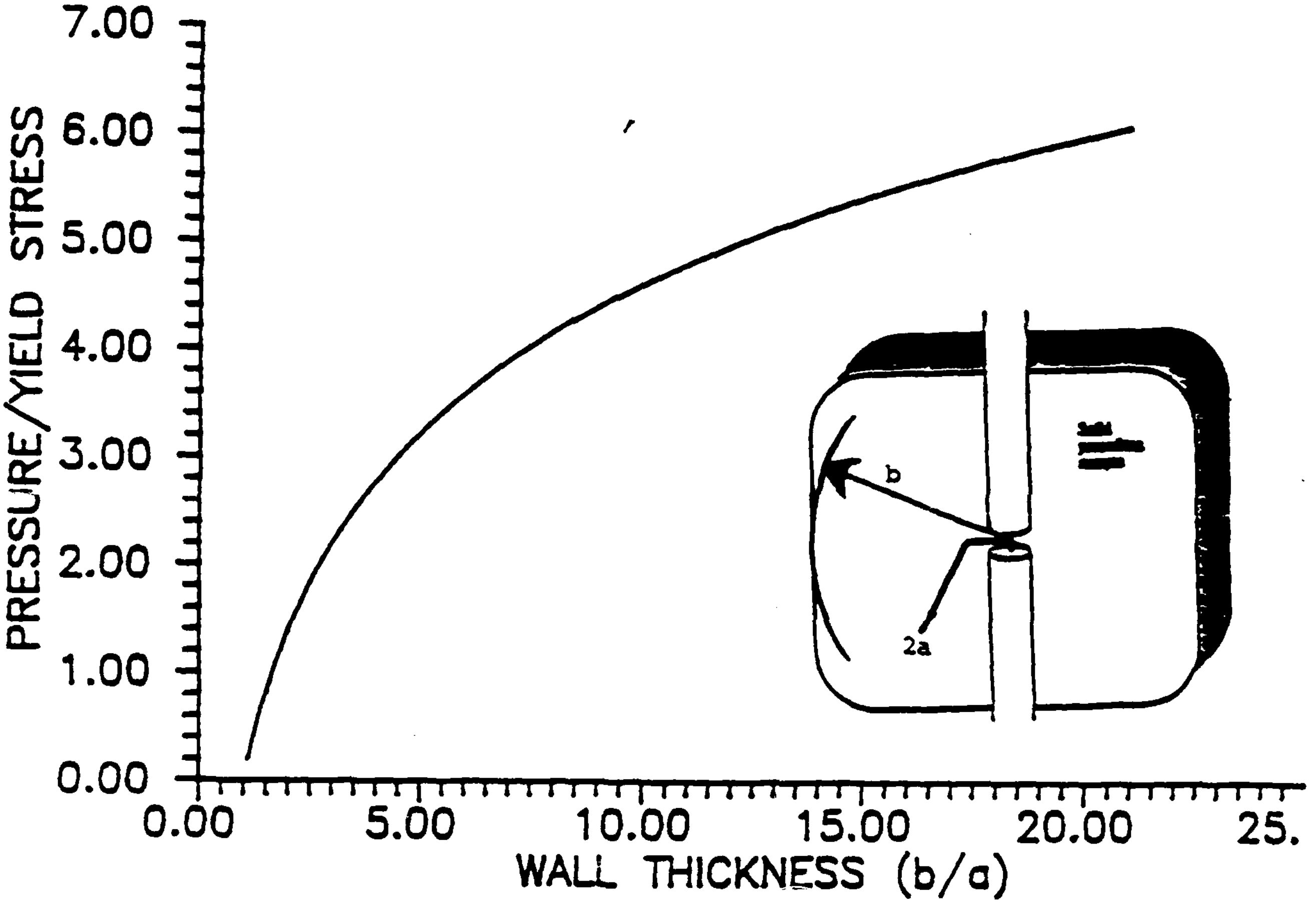
- p(t) at hot spot (see below)
- first light (other than spark)
- resistance change of hot wire (heating by combustion or breaking)

REQUIRED PARAMETRIC VARIATIONS FOR EACH PROPELLANT

- Gap width or hot wire length
- Duration of input before ignition
- Ramp vs step input (rate in general)
- Humidity and T ($\frac{1}{2}CV_0^2$ for ignition decreases with increasing T – Larson et al., 1986 PSHS)
- Damage (spark hot spots only)
  - Cast abutting electrodes and then retract to desired gap
  - Multiple sparks to same sample
  - Needle electrodes pushed into precast sample (Hodges & McCoy, 1989 PSHS)
- Confinement through
  - Sample holder (Brown et al., Bur Mines 1953, Larson et al., 1986 PSHS)
  - Pressure vessel (Hodges & McCoy, 1989 PSHS)
  - Vary sample size in unconfined test

EFFECT OF SAMPLE SIZE ON CONFINEMENT, ASSUMING

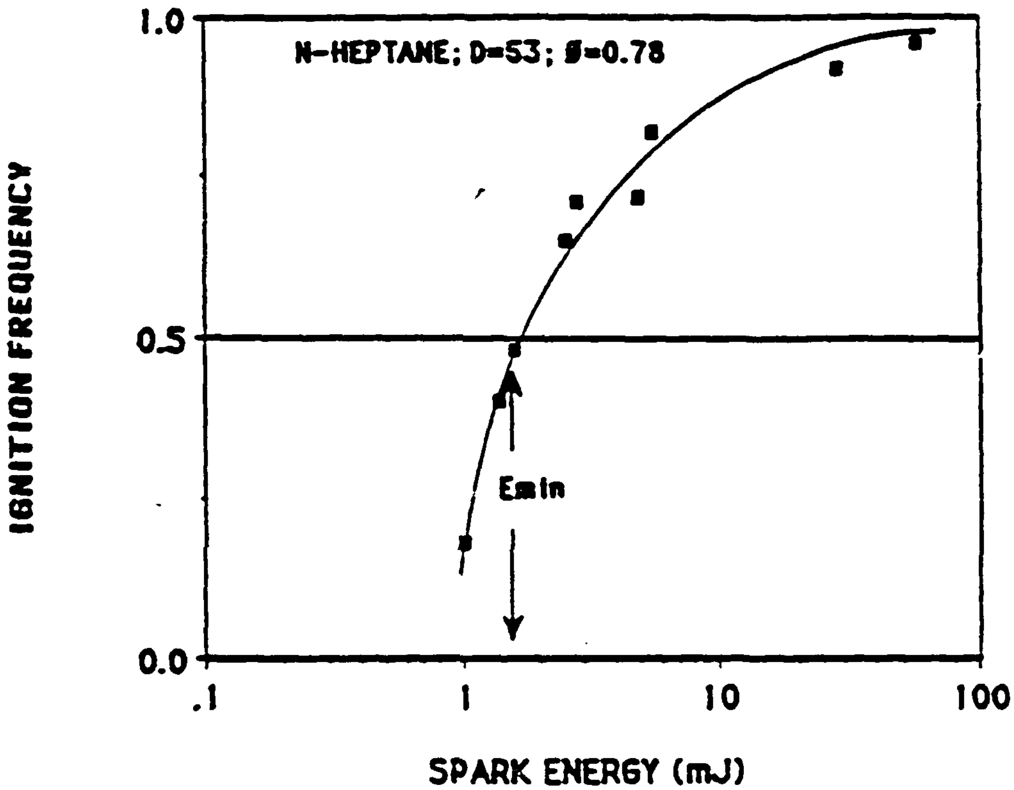
- Sample material is linearly elastic/perfectly plastic
- Hot spot is a spherical cavity of diameter 2a (O(2-9 mm))
- Sample is modelled as the largest sphere inside the cube of propellant (diameter 2b O(40 mm))



DETERMINATION OF $E_{min} = E_{50}$

- For each set of parameters above address sample inhomogeneity by repeated tests on "identical" specimens (O(25) replications based on Coffey's drop-weight impact work at NSWC)

- Make probit curves to get E_{50}



- E_{50} at optimum gap width and duration is E_{min}. Repeat for other parametric variations

CLOSING OBSERVATIONS

- p(t) in hot spot from hollow, grease-filled electrode or separate tubing (Kistler) will address severity as well as initiation time
- Gap widths, O(mm) >> scale of propellant heterogeneity, O(10 to 100 μm)
- Thus imposed hot spot much larger than hot spots resulting from external stimulus, and ignition mechanisms may be different
- Nevertheless E_{min} is
  - required for risk/hazard analysis
  - property of the material
  - proposed by analogy with well-established procedures for premixed gases and fuel sprays

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ARO WORKSHOP
ESD Ignition of Composite Solid Propellants
April 18-19, 1989
Vanderbilt University
Nashville, Tennessee 37235

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